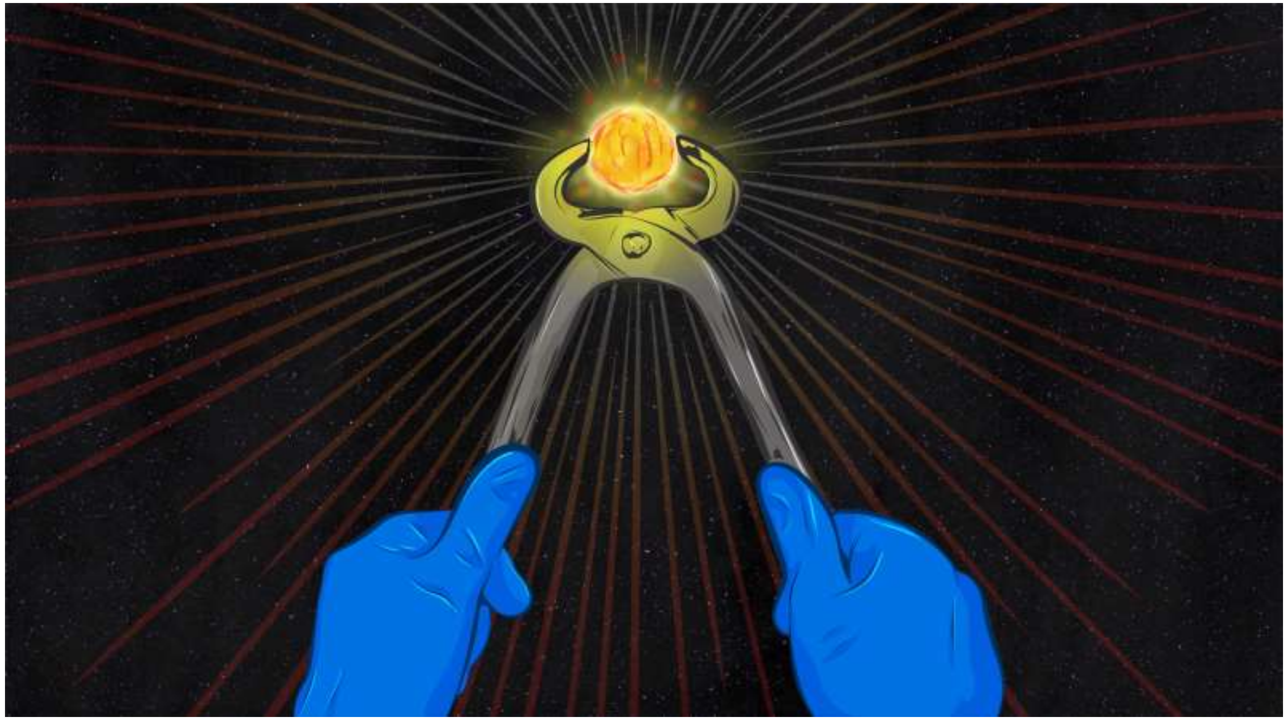
Fusion Energy and MIT's pathway to accelerated demonstration with high magnetic field tokamaks

PSFC



Art Work by Sam Woolley, thewoolley.com

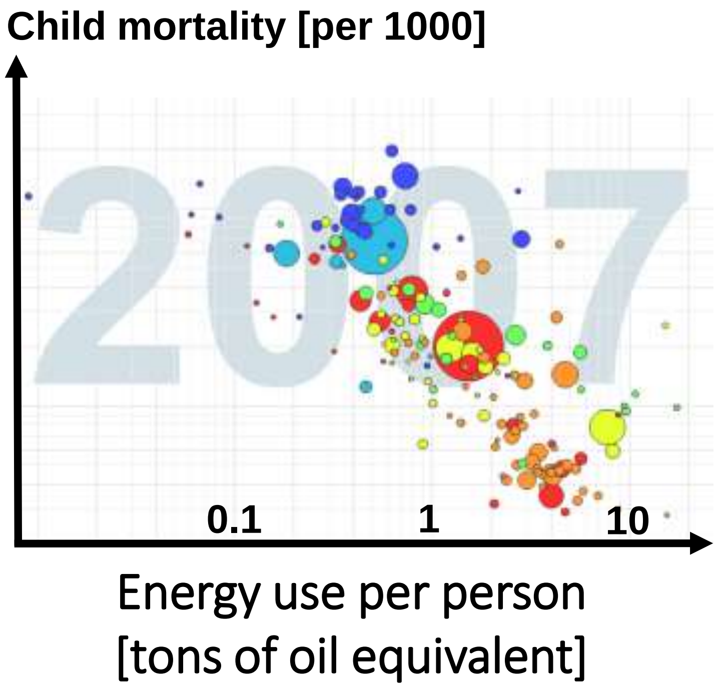
Zach Hartwig

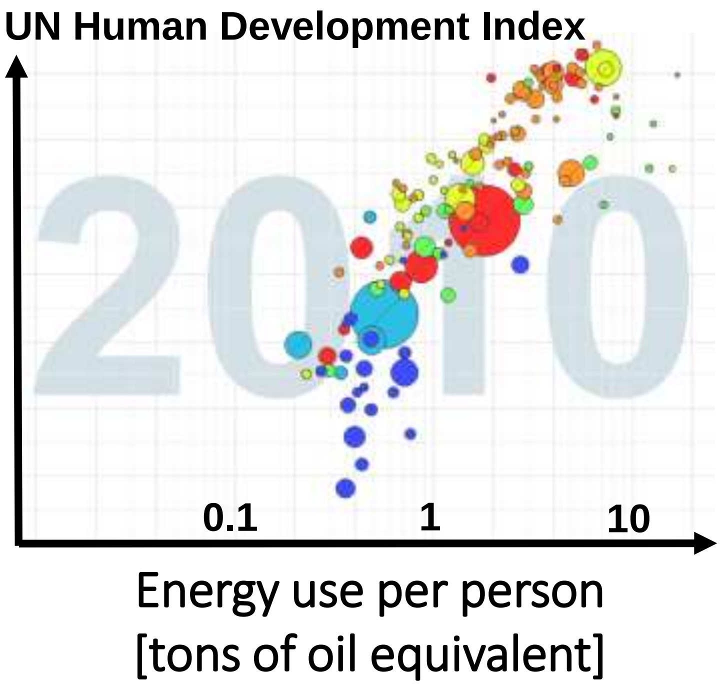
- Nuclear Science and Engineering
- Plasma Science and Fusion Center

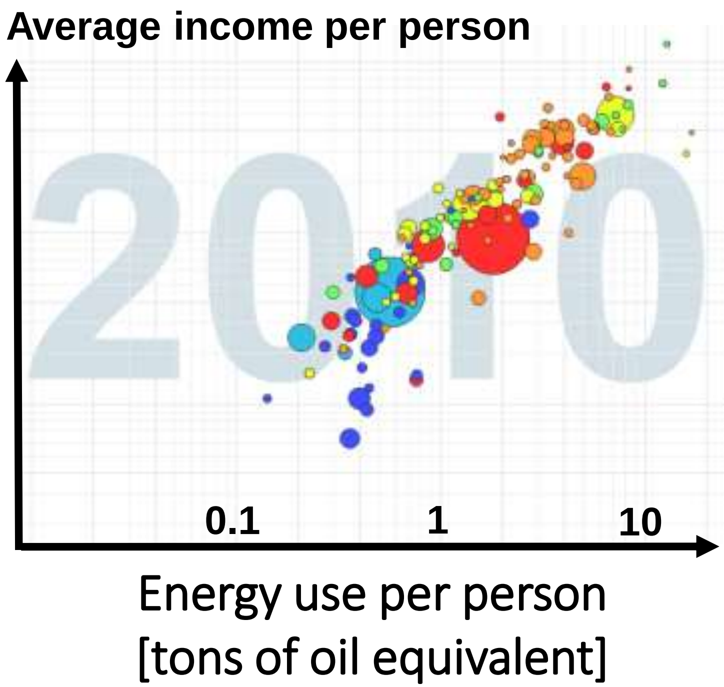
Many thanks

- Dan Brunner, Bob Mumgaard, Brandon Sorbom
- Todd Rider

Energy use correlates with many quality-of-life metrics…







Statistics and plots from gapminder.org/tools

Unfortunately, so does CO_2 production

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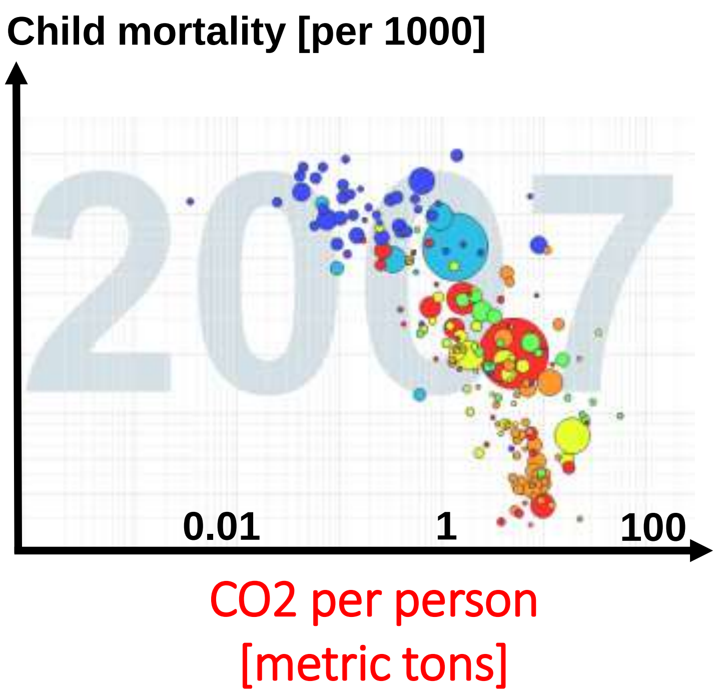
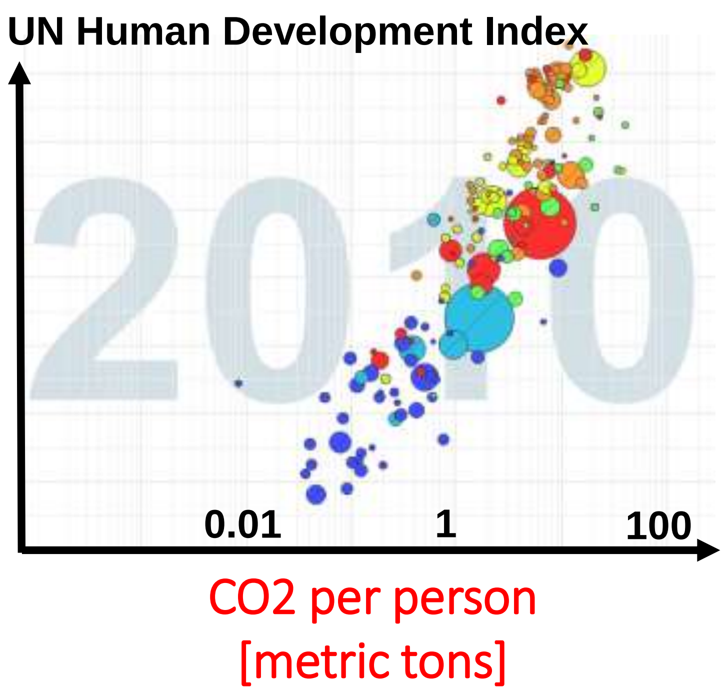
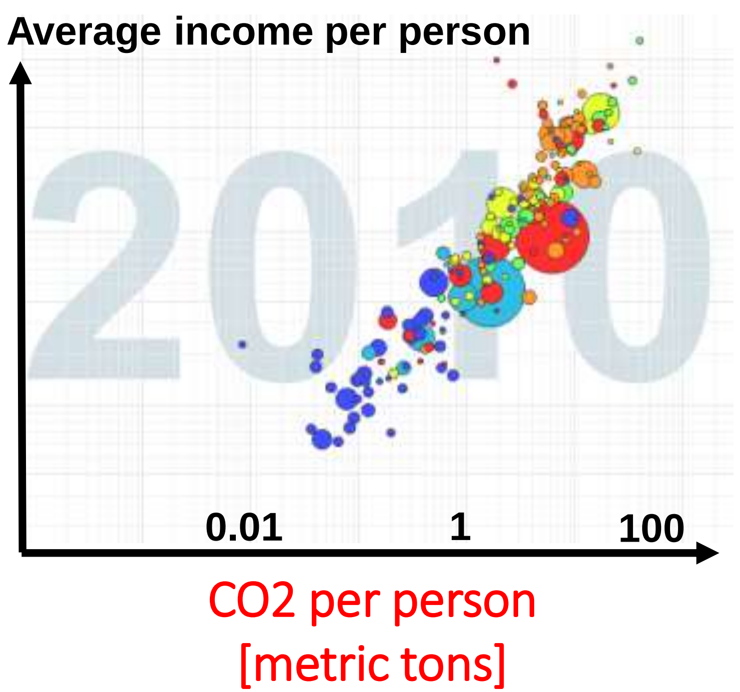


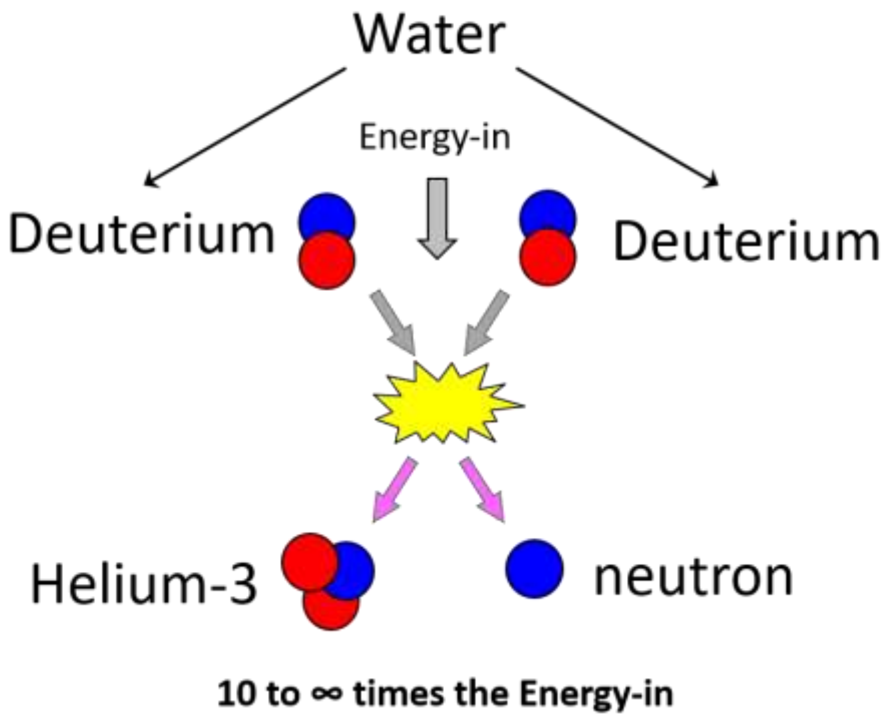




The reality is that every single nation that
has industrialized and made a better life for
its citizens has done so at the expense of the climate

The term “fusion energy” describes a basic physical process for producing energy; the complications come from the approach!

- Fusion is a fundamental process that combines two nuclei and releases energy. Its immense promise has compelled its pursuit for almost 60 years…



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Advantages of fusion over fossil fuels:

- No carbon, SOx/NOx, particulate emissions
- Inexhaustible fuel supply
  - Thousands to millions of years
- Fuels equally accessible to all
- No large scale extraction+ transport of fuels

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Advantages of fusion over other renewables:

- High power density land use
- High power density materials use
- On when it is wanted
- Site where it is needed
- Plugs into established grids

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Advantages of fusion over nuclear fission energy:

- No chain reaction = no possibility of a melt down
- No long-lived nuclear waste for deep storage
    - Lower level activation of components
- Low proliferation risk
    - No need for fissile material (*e.g.* U, Pu)
    - Non-fusion clandestine use highly infeasible

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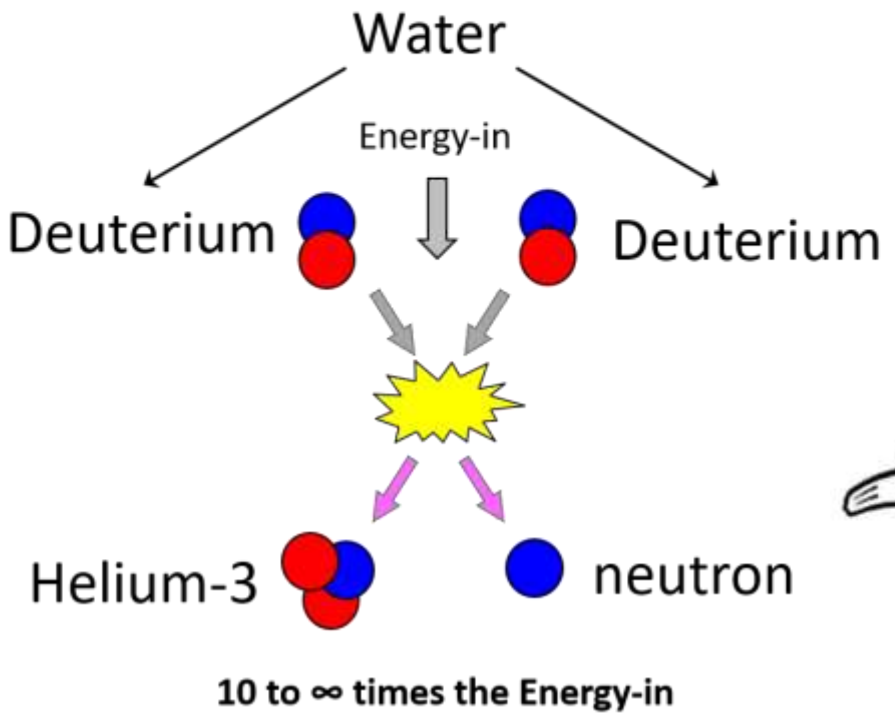

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- Fusion is a fundamental process that combines two nuclei and releases energy. It's immense promise has compelled its pursuit for almost 60 years…

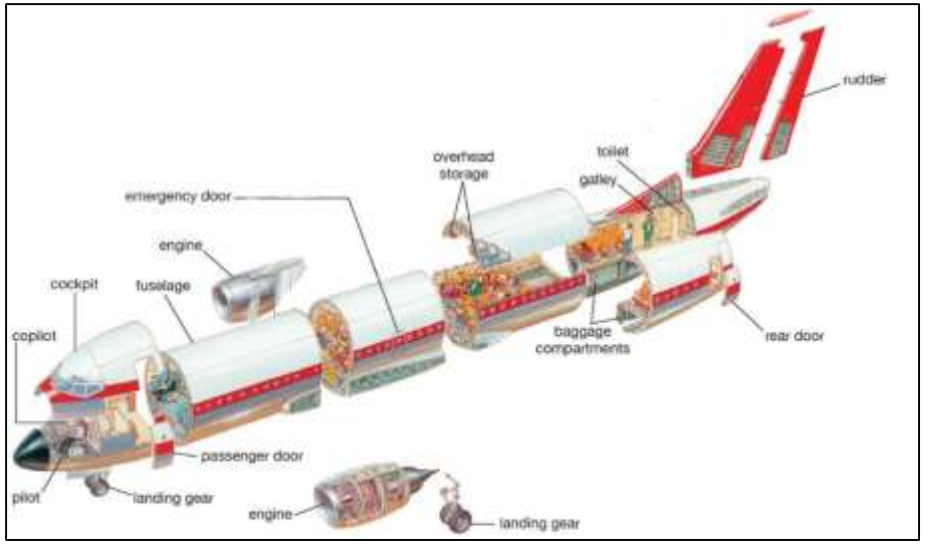
- …but there are so many approaches to fusion energy that it can be extremely difficult to distinguish "winners" from "long-shots" from "losers".
  - This is true of the layperson, interested reader, investor, and even fusion scientist!

- Fusion is a fundamental process that co... It’... pu...
- …l... fu... di... “l...

The ability to evaluate complicated technology is about asking the right questions

Imagine the year is 1905 … which do you invest in?

Pitch: It’s deluxe transportation!
You : Yes, but … where’s your wing?



A physics problem

Pitch: We worked out aerodynamic principles!
You : Yes, but … how does it transport people?

An engineering problem

The term "fusion energy" describes a basic physical process for producing energy; the complications come from the approach!

- Fusion is a fundamental process that combines two nuclei and releases energy. It's immense promise has compelled its pursuit for almost 60 years…

- …but there are so many approaches to fusion energy that it can be extremely difficult to distinguish "winners" from "long-shots" from "losers".

1. The primary purpose of this talk is to gives you tools to evaluate fusion energy approaches. Learn to pick a winner!

2. The secondary purpose is to motivate why the PSFC is using high-magnetic field tokamaks to achieve fusion energy on relevant timescales

We'll develop 3 rules as answers to 3 key questions – exploring the relevant physics as we go – and then put them to use.

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Part 1 : Developing "The Rules" for assessing fusion energy concepts

- Q1: What are the viable fusion fuels and how do they affect the approach?
- Q2: What are the physical conditions required to achieve net fusion energy?
- Q3: What fusion energy approaches exist and how should they be evaluated?

Part 2 : MIT's accelerated pathway to demonstrate net fusion energy

Part 1 : Developing "The Rules" for assessing fusion energy concepts

- Q1: What are the viable fusion fuels and how do they affect the approach?
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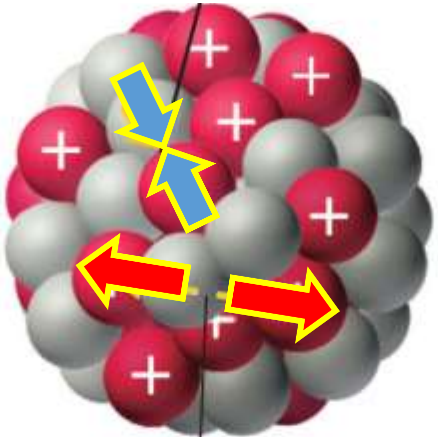
Part 2 : MIT's accelerated pathway to demonstrate net fusion energy

Rearranging the neutrons and protons that form the building blocks of atomic nuclei can release enormous amounts of energy

- Protons and neutrons are held together in the nucleus by the **strong nuclear force**, which overcomes **Coulomb repulsion**

Strong nuclear force

n↔n n↔p p↔p



Coulomb repulsion

p↔p

Rearranging the neutrons and protons that form the building blocks of atomic nuclei can release enormous amounts of energy

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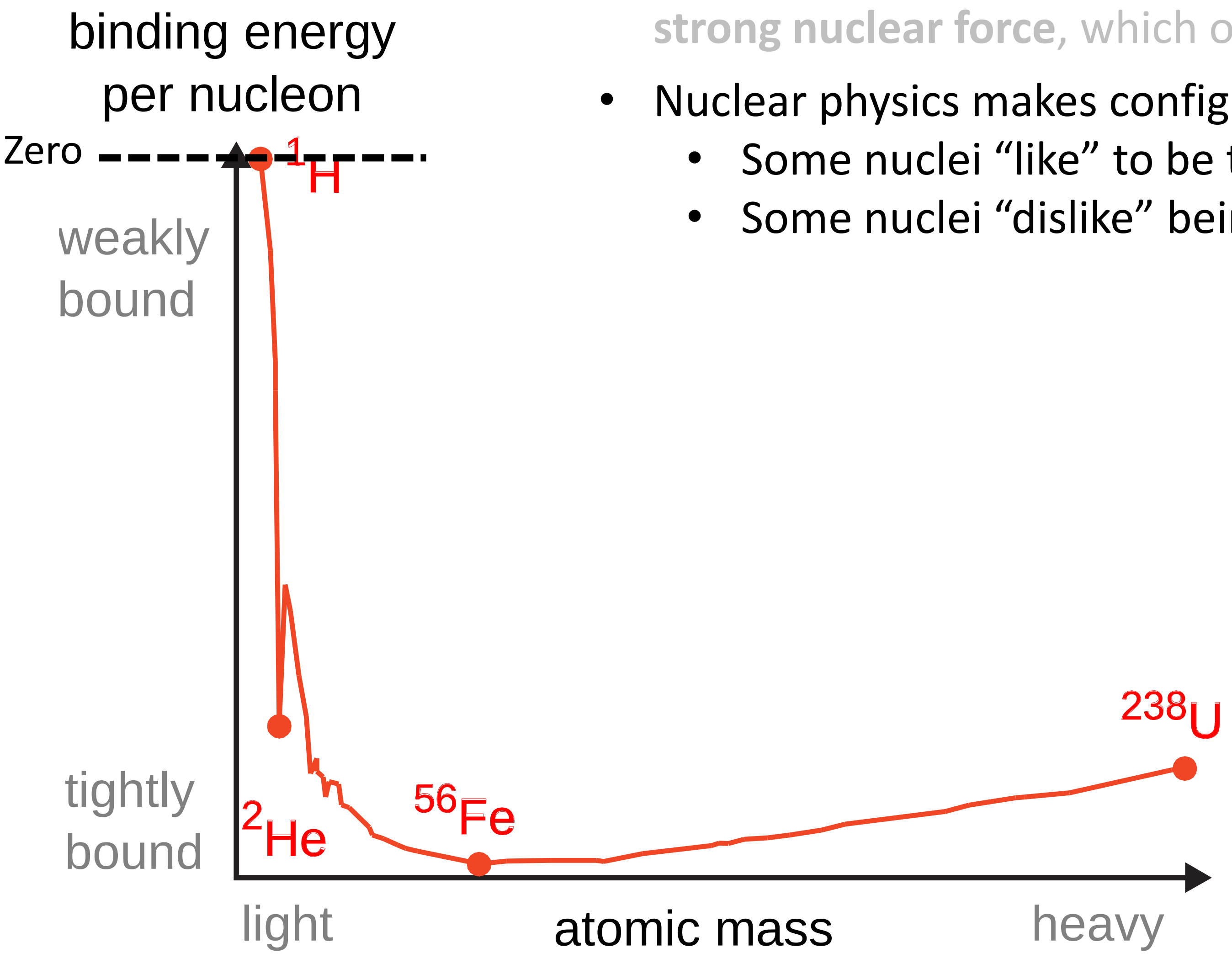

- Protons and neutrons are held together in the nucleus by the **strong nuclear force**, which overcomes **Coulomb repulsion**
- Nuclear physics makes configurations of protons and neutrons different:
  - Some nuclei “like” to be together and require less “binding energy”
  - Some nuclei “dislike” being together and require more “binding energy”

Rearranging the neutrons and protons that form the building blocks of atomic nuclei can release enormous amounts of energy

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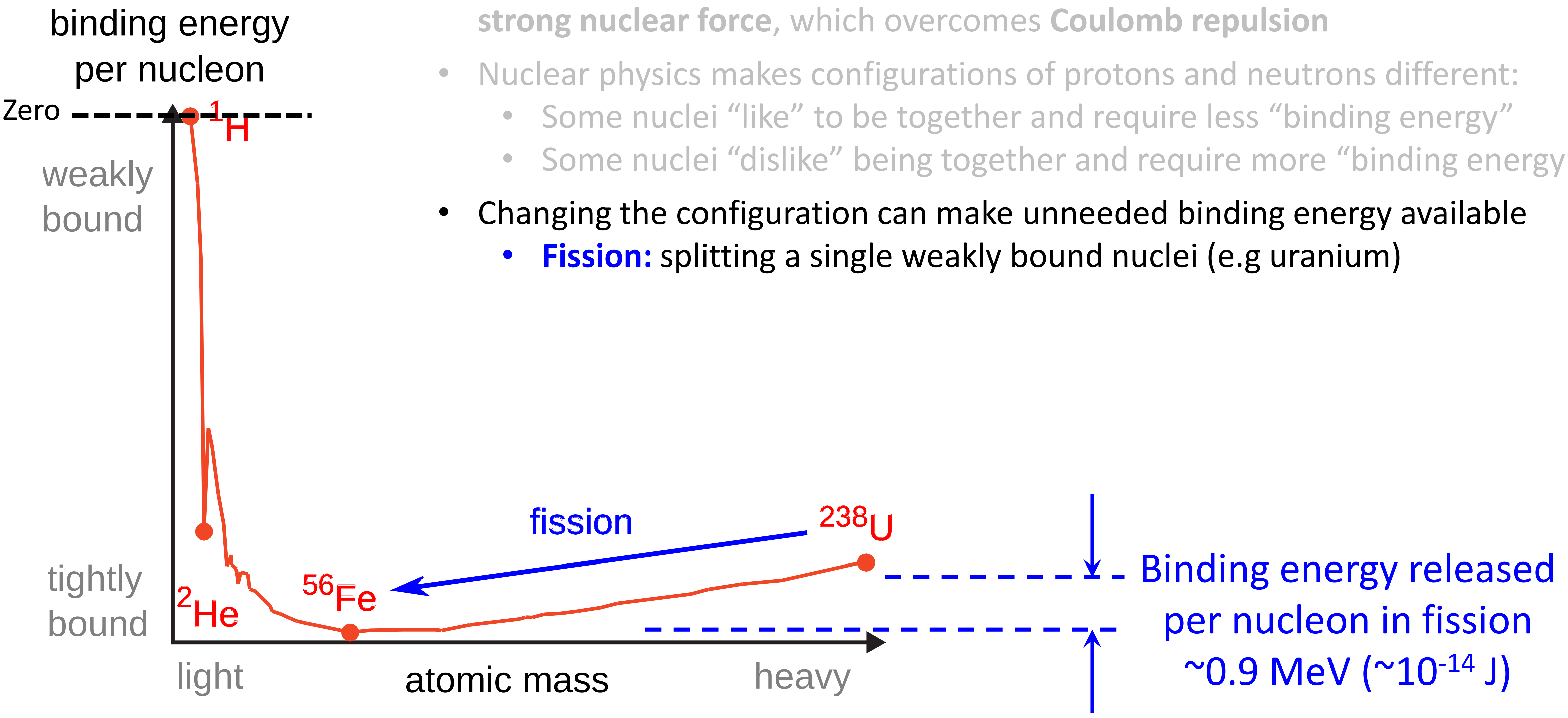

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- Changing the configuration can make unneeded binding energy available
  - **Fission:** splitting a single weakly bound nuclei (e.g uranium)

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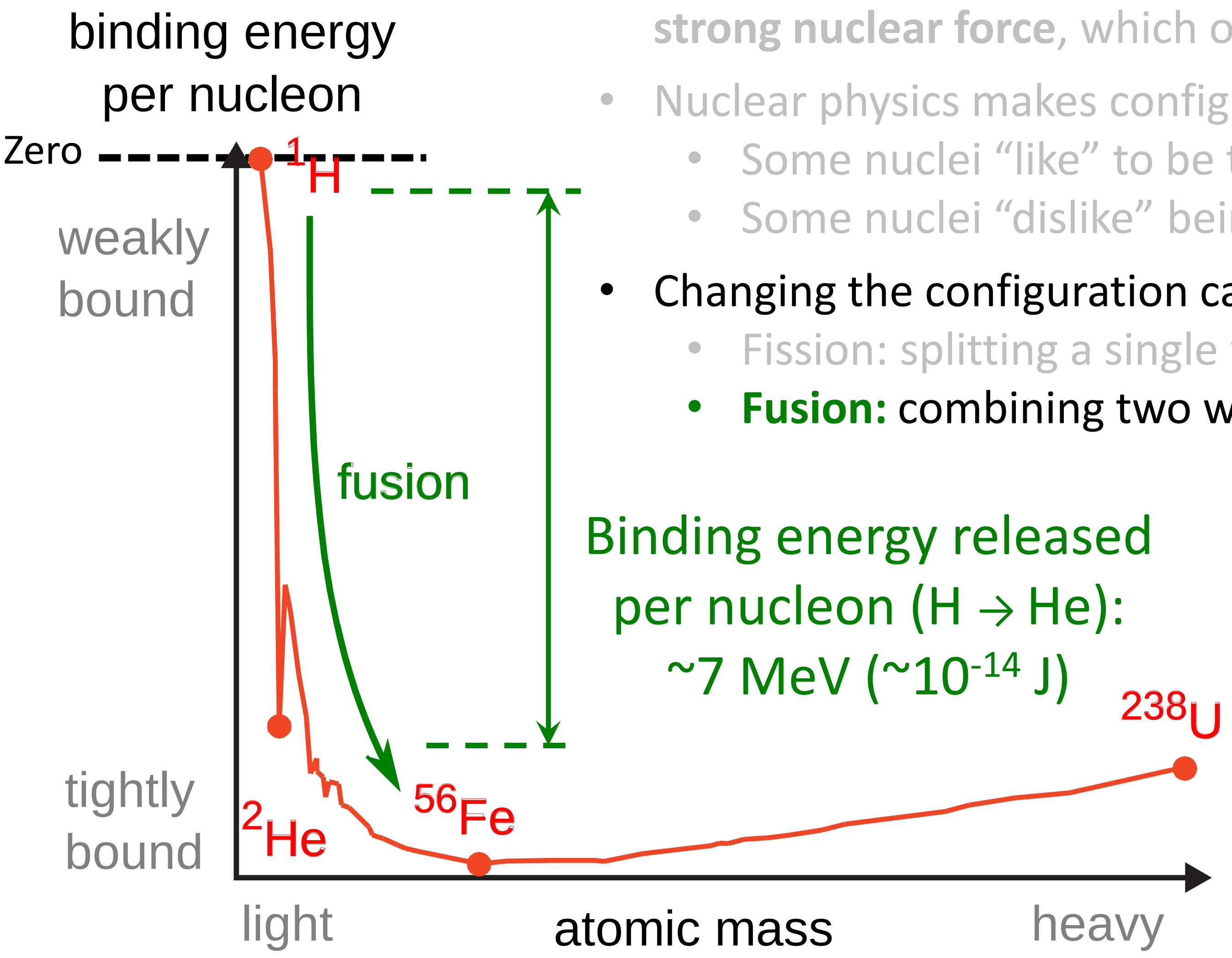

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- Changing the configuration can make unneeded binding energy available
  - Fission: splitting a single weakly bound nuclei (*e.g* uranium)
  - **Fusion:** combining two weakly bound nuclei (*e.g.* hydrogen into helium)

Two basic physical quantities fundamentally set fusion fuel viability: (1) the reaction energetics (input, output); (2) the reaction probability

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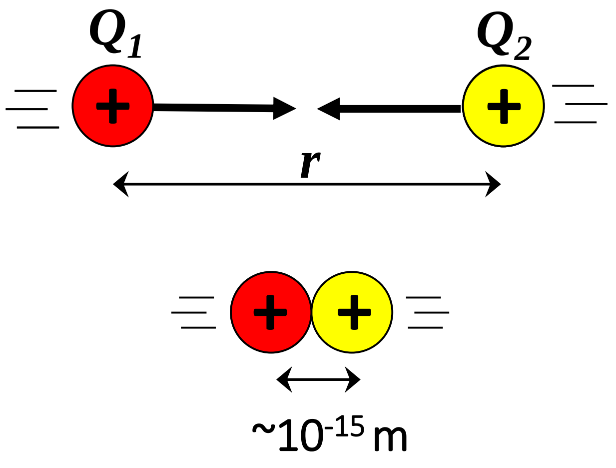
Reaction energetics

Reaction probability

Input energy:

The energy provided to ions to overcome the Coulomb barrier must be reasonably achievable



$$U = \frac{1}{4\pi\epsilon_0}\frac{Q_1 Q_2}{r}$$

Two basic physical quantities fundamentally set fusion fuel viability:
(1) the reaction energetics (input, output); (2) the reaction probability

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Reaction energetics

Reaction probability

Input energy:
The energy provided to ions to overcome the Coulomb barrier must be reasonably achievable

$$U = \frac{1}{4\pi\epsilon_0}\frac{Q_1 Q_2}{r}$$

Output energy:
Energy released from reaction must not only be net positive but sufficiently large enough

Two basic physical quantities fundamentally set fusion fuel viability: (1) the reaction energetics (input, output); (2) the reaction probability

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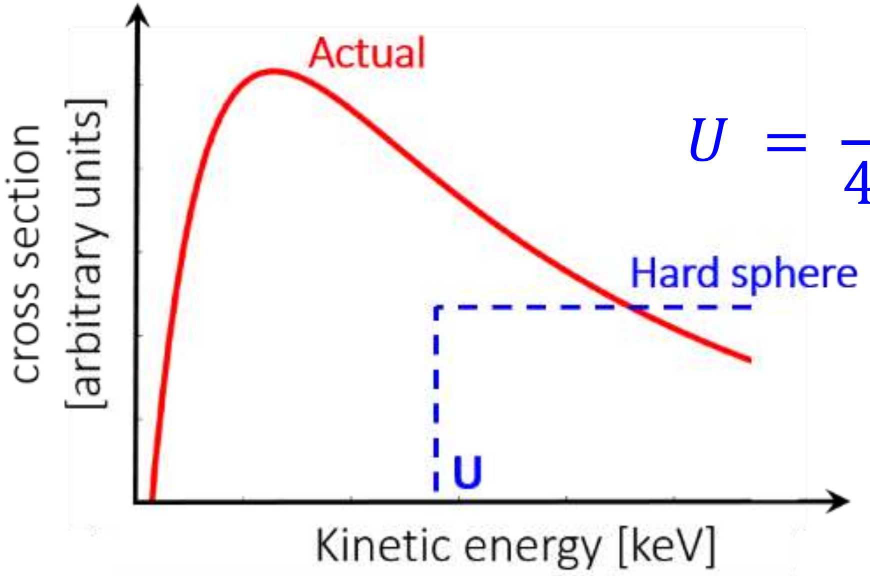
Reaction energetics

Reaction probability

Fusion reaction cross section

The probability that two nuclei will fuse must be sufficiently high. Probability is not simple but governed by quantum and nuclear physics



$$U = \frac{1}{4\pi\epsilon_0}\frac{Q_1 Q_2}{r}$$

Reaction energetics

Reaction probability

The ideal fusion fuel will have:

1. Low input energy to induce a fusion reaction
   - Technologically easier to achieve
   - Economically requires less input energy

2. A high probability of fusion

3. High output energy for converting to electricity

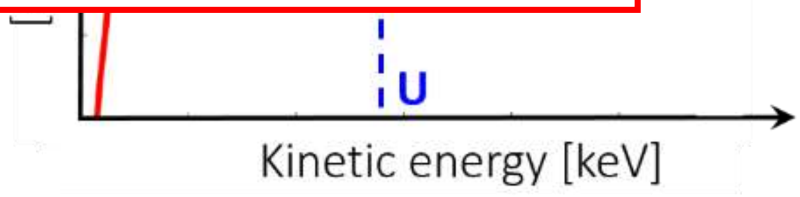
use must

simple

ar physics

$$U = \frac{1}{4\pi\epsilon_0}\frac{Q_1 Q_2}{r}$$

d sphere



Let's take a closer look at combining nuclides and assess what combinations might be attractive for fusion fuels

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Theoretically feasible

Borderline

Not feasible

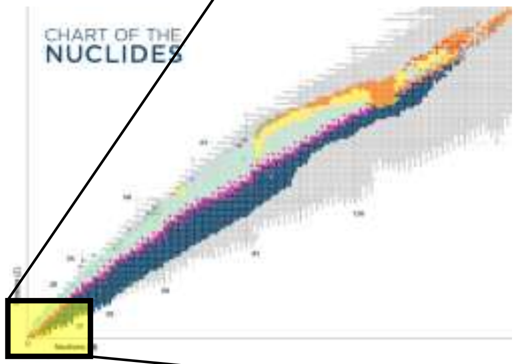
Neglect:

- Nuclei with $\tau_{1/2}$ < 1 min
- 3-body fusion

Input nucleus 2

Input nucleus 1

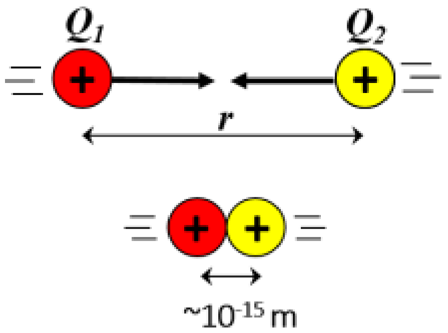
Input nucleus 1 \ Input nucleus 2	^{1}H	^{2}H	^{3}H	^{3}He	^{4}He	^{6}Li
^{1}H						
^{2}H						
^{3}H						
^{3}He						
^{4}He						
^{6}Li						
^{7}Li						
^{7}Be						
^{9}Be						
^{10}Be						
^{10}B						
^{11}B						
^{11}C						
^{12}C						
^{13}C						
^{14}C						



The fusion reaction energy and probability dramatically restrict viable fusion fuels

Reason

Coulomb barrier too high



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	^{1}H	^{2}H	^{3}H	^{3}He	^{4}He	^{6}Li
^{1}H						
^{2}H						
^{3}H						
^{3}He						
^{4}He						
^{6}Li						
^{7}Li						
^{7}Be						
^{9}Be						
^{10}Be						
^{10}B						
^{11}B						
^{11}C						
^{12}C						
^{13}C						
^{14}C						

$Z_1Z_2 \geq 8$ Coulomb barrier is too high

$Z_1Z_2 \geq 7$ Coulomb barrier is too high

The fusion reaction energy and probability dramatically restrict viable fusion fuels

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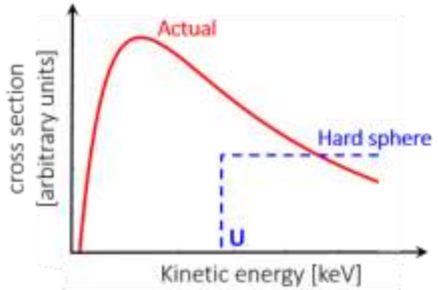
Reason

Cross section too low



Input nucleus 1 \ Input nucleus 2	^{1}H	^{2}H	^{3}H	^{3}He	^{4}He	^{6}Li
^{1}H	1.4 MeV $>10^{-25}$ b at >1 MeV					
^{2}H	5.5 MeV 10^{-6} b at 1 MeV					
^{3}H	-0.76 MeV					
^{3}He	19.8 MeV Negligible					
^{4}He	Negligible	1.5 MeV 10^{-7} b at 700 keV			Negligible except stellar 3α fusion	
^{6}Li				16.9 MeV >0.03 b at >1 MeV	-2.1 MeV	
^{7}Li	17.3 MeV 0.006 b at 400 keV					
^{7}Be	0.14 MeV 2×10^{-6} b at 600 keV					
^{9}Be						
^{10}Be						
^{10}B	1.1 MeV 0.2 b at 1 MeV					
^{11}B						
^{11}C						
^{12}C	1.9 MeV 1×10^{-4} b at 400 keV					
^{13}C	7.6 MeV 0.001 b at 500 keV					
^{14}C						

$Z_1Z_2 \geq 8$ Coulomb barrier is too high

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Theoretically feasible

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The fusion reaction energy and probability dramatically restrict viable fusion fuels

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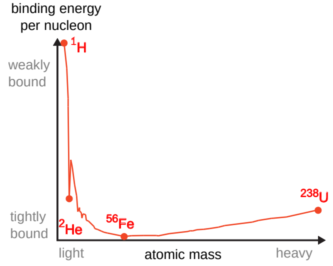
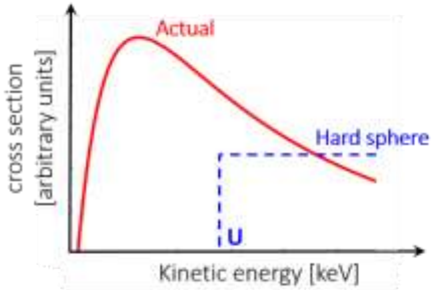
Reason

Energy out + cross section are weak





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^{3}He	19.8 MeV Negligible		13 MeV >0.2 b at >450 keV	12.9 MeV >0.15 b at >3 MeV		
^{4}He	Negligible	1.5 MeV 10^{-7} b at 700 keV	2.5 MeV	1.6 MeV	Negligible except stellar 3α fusion	
^{6}Li	4.0 MeV 0.2 b at 2 MeV	5.0 MeV 0.1 b at 1 MeV	16.1 MeV	16.9 MeV >0.03 b at >1 MeV	-2.1 MeV	
^{7}Li	17.3 MeV 0.006 b at 400 keV	15.1 MeV >0.5 b at >1 MeV	8.9 MeV >0.2 b at >4 MeV	11-18 MeV	8.7 MeV 0.4 b at 500 keV	
^{7}Be	0.14 MeV 2×10^{-6} b at 600 keV	16.8 MeV	10.5 MeV	11.3 MeV	7.5 MeV 0.3 b at 900 keV	
^{9}Be	2.1 MeV 0.4 b at 300 keV	7.2 MeV >0.1 b at >1 MeV	9.6 MeV >0.1 b at >2 MeV		5.7 MeV 0.3 b at 1.3 MeV	
^{10}Be						
^{10}B	1.1 MeV 0.2 b at 1 MeV	9.2 MeV >0.2 b at >1 MeV				
^{11}B	8.7 MeV 0.8 b at 600 keV	13.8 MeV >0.1 b at >1 MeV	8.6 MeV			
^{11}C						
^{12}C	1.9 MeV 1×10^{-4} b at 400 keV					
^{13}C	7.6 MeV 0.001 b at 500 keV					
^{14}C						

$Z_1Z_2\geq8$ Coulomb barrier is too high

$Z_1Z_2\geq7$ Coulomb barrier is too high

The fusion reaction energy and probability dramatically restrict viable fusion fuels: only ~0.2% of all known isotopes even approach viability!

PSFC

Theoretically feasible | Borderline | Not feasible

Neglect:
- Nuclei with $\tau_{1/2}$ < 1 min
- 3-body fusion

Input nucleus 2 (columns) / **Input nucleus 1** (rows)

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^{2}H	5.5 MeV 10^{-6} b at 1 MeV	3.65 MeV >0.1 b at >150 keV				
^{3}H	-0.76 MeV	17.6 MeV 5 b at 80 keV	11.3 MeV 0.16 b at 1 MeV			
^{3}He	19.8 MeV Negligible	18.3 MeV 0.8 b at 300 keV	13 MeV >0.2 b at >450 keV	12.9 MeV >0.15 b at >3 MeV		
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^{10}Be						
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^{11}B	8.7 MeV 0.8 b at 600 keV	13.8 MeV >0.1 b at >1 MeV	8.6 MeV			
^{11}C						
^{12}C	1.9 MeV 1x10^{-4} b at 400 keV					
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^{14}C						

$Z_1Z_2 \geq 8$ Coulomb barrier is too high

$Z_1Z_2 \geq 7$ Coulomb barrier is too high

Only 4 fusion fuels are considered practical for energy production. Their feasibility rank depends most strongly on required input energy.

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Fuel (Input)	Exhaust (output)	Energy gain (MeV)	Cross section (barn)
D + T	^{4}He + n	17.6	5.0 @ 80 keV
D + D	T + p (50%) ^{3}He + n (50%)	3.7	0.1 @ 150 keV
D + ^{3}He	^{4}He + p	18.3	0.8 @ 300 keV
p + ^{11}B	3 ^{4}He	8.7	0.8 @ 600 keV

Because the probability of scattering dominates fusion for all fuels, the fuel must be arranged to allow many fusion attempts with fuel loss!

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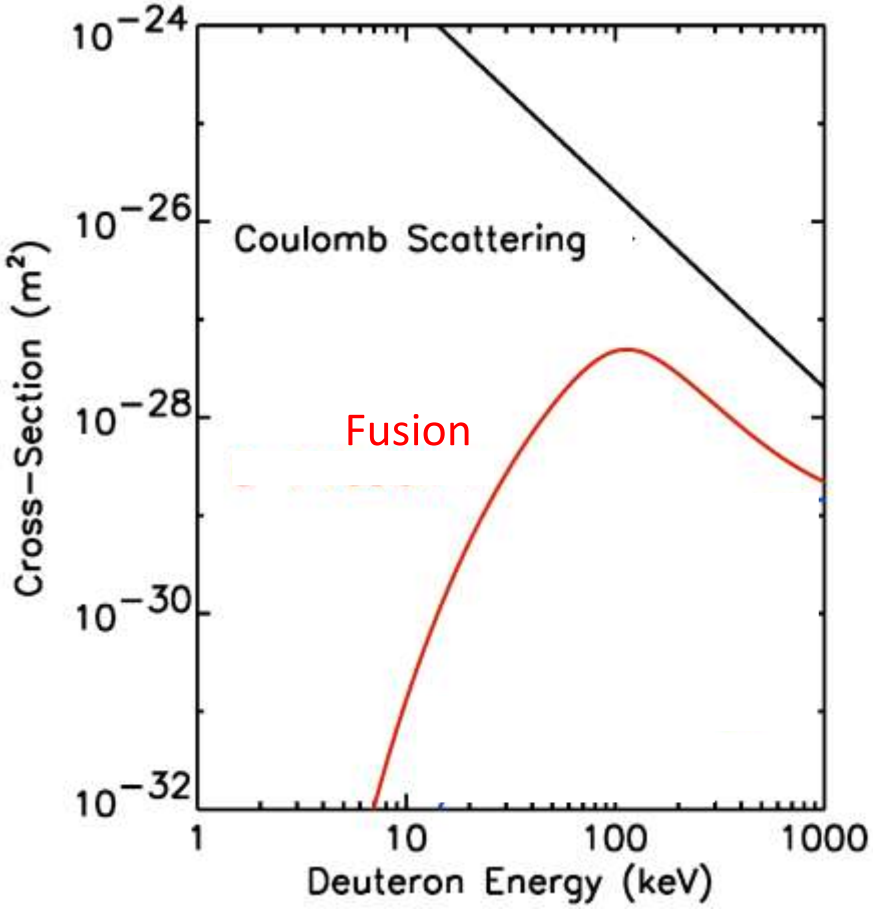
- Coulomb scattering provides a fundamental challenge to getting enough fusion reactions

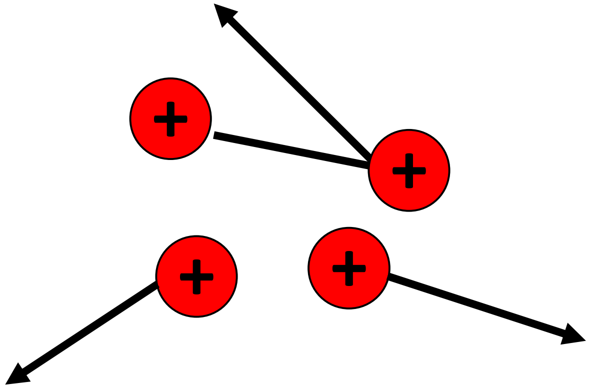
The bane of fusion energy



Because the probability of scattering dominates fusion for all fuels, the fuel must be arranged to allow many fusion attempts with fuel loss!

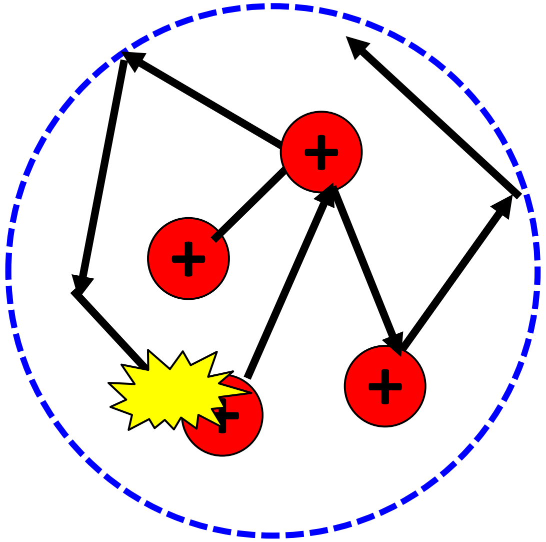
- Coulomb scattering provides a fundamental challenge to getting enough fusion reactions

- Overcoming Coulomb scattering requires keeping fuel around long enough to get many chances. We call this “confinement”.



No confinement:

- Particles scatter and are lost
- No fusion occurs



Ideal confinement

- Who cares if particles scatter?
- Fusion occurs eventually

Because the probability of scattering dominates fusion for all fuels, the fuel must be arranged to allow many fusion attempts with fuel loss!

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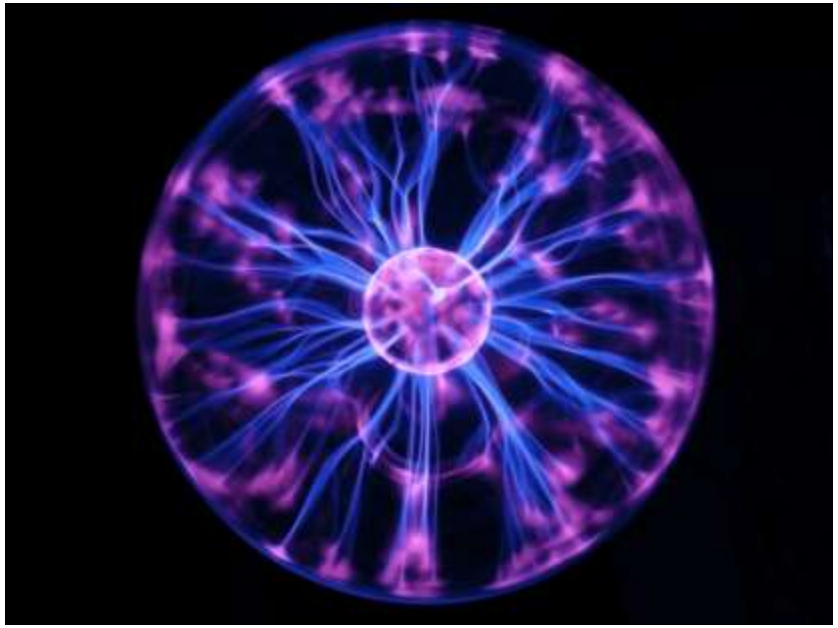
- Coulomb scattering provides a fundamental challenge to getting enough fusion reactions
- Overcoming Coulomb scattering requires keeping fuel around long enough to get many chances. We call this “confinement”.
- Confinement of particles at these energies creates the conditions of a plasma
  - Ionized gas (“fluids” of electrons and ions)
  - Dominated by collective behavior
  - Energy of the system is best described as a temperature



Only 4 fusion fuels are considered practical for energy production. Their feasibility rank depends most strongly on required temperature

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Rank	Fuel (Input)	Exhaust (output)	Energy gain (MeV)	Peak reactivity [m^{-3} s^{-1}]	Temperature [K / C / F]
1	D + T	^{4}He + n	17.6	1×10^{-18} @ 15 keV	175,000,000
2	D + D	T + p (50%) ^{3}He + n (50%)	3.7	1×10^{-20} @ 20 keV	232,000,000
3	D + ^{3}He	^{4}He + p	18.3	2×10^{-20} @ 50 keV	580,000,000
4	p + ^{11}B	3 ^{4}He	8.7	3×10^{-21} @ 150 keV	1,740,000,000

Primary condition: the required temperature must be practically achievable

- This turns out to be so important as to determine the ranking

Only 4 fusion fuels are considered practical for energy production. Their feasibility rank depends most strongly on required input energy

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Rank	Fuel (Input)	Exhaust (output)	Energy gain (MeV)	Peak reactivity [m^{-3} s^{-1}]
1	D + T	^{4}He + n	17.6	1×10^{-18} @ 15 keV
2	D + D	T + p (50%) ^{3}He + n (50%)	3.7	1×10^{-20} @ 20 keV
3	D + ^{3}He	^{4}He + p	18.3	2×10^{-20} @ 50 keV
4	p + ^{11}B	3 ^{4}He	8.7	3×10^{-21} @ 150 keV

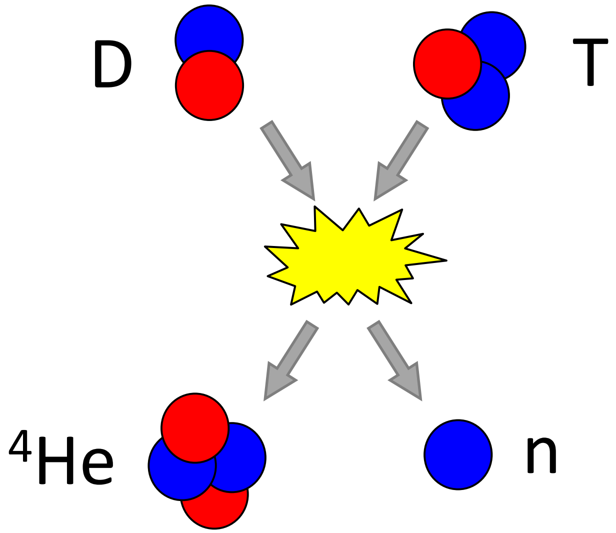
Primary condition: the required temperature must be practically achievable

- This turns out to be so important as to determine the ranking

Secondary condition: the reactivity and energy gain must be large

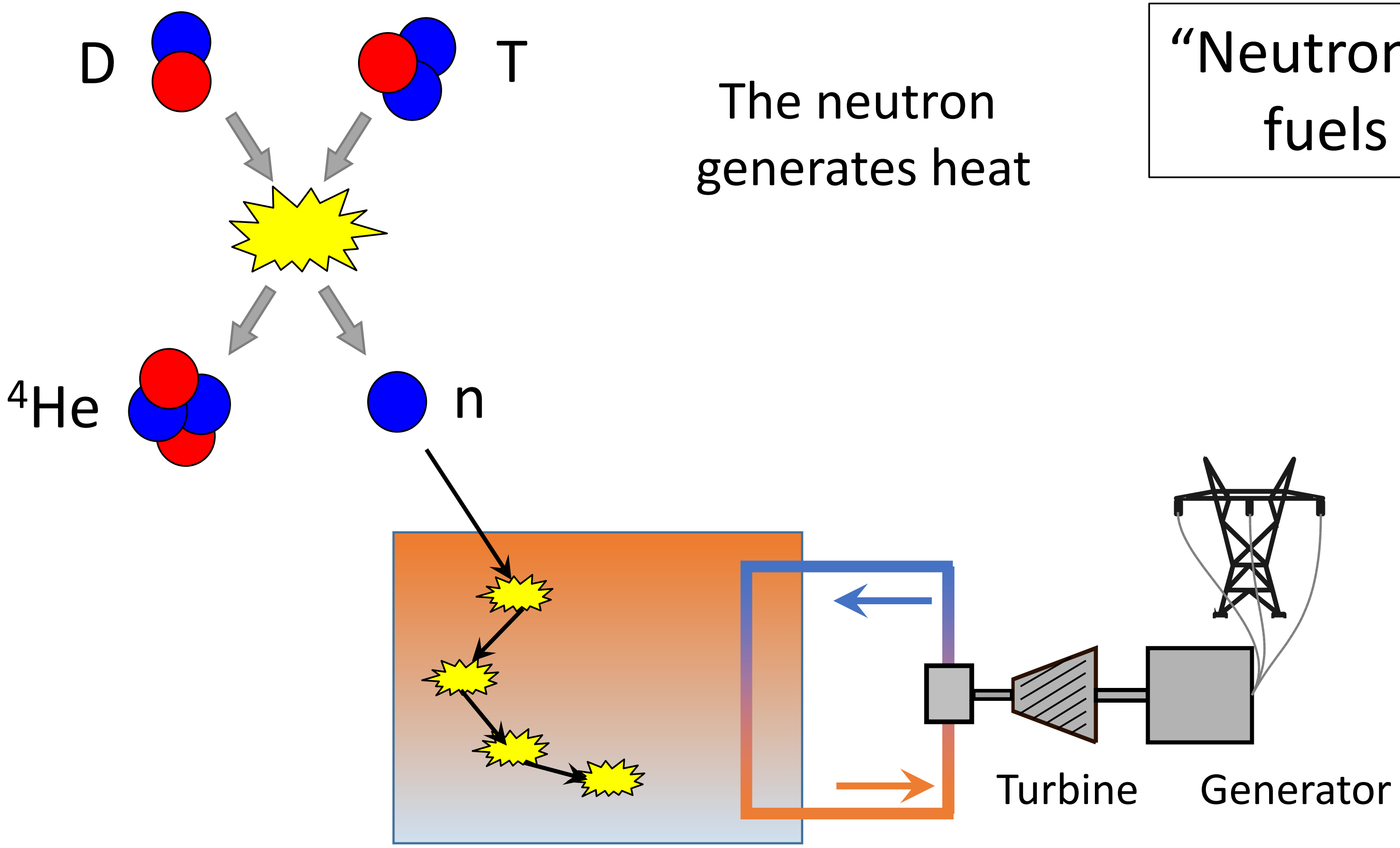
- These conditions are necessary but not sufficient

The exhaust products of the viable fusion fuels determine how fusion energy is converted to electricity.



"Neutronic" fuels

The exhaust products of the viable fusion fuels determine how fusion energy is converted to electricity.



The neutron generates heat

“Neutronic” fuels

Heat conversion and fuel generation

The exhaust products of the viable fusion fuels determine how fusion energy is converted to electricity.

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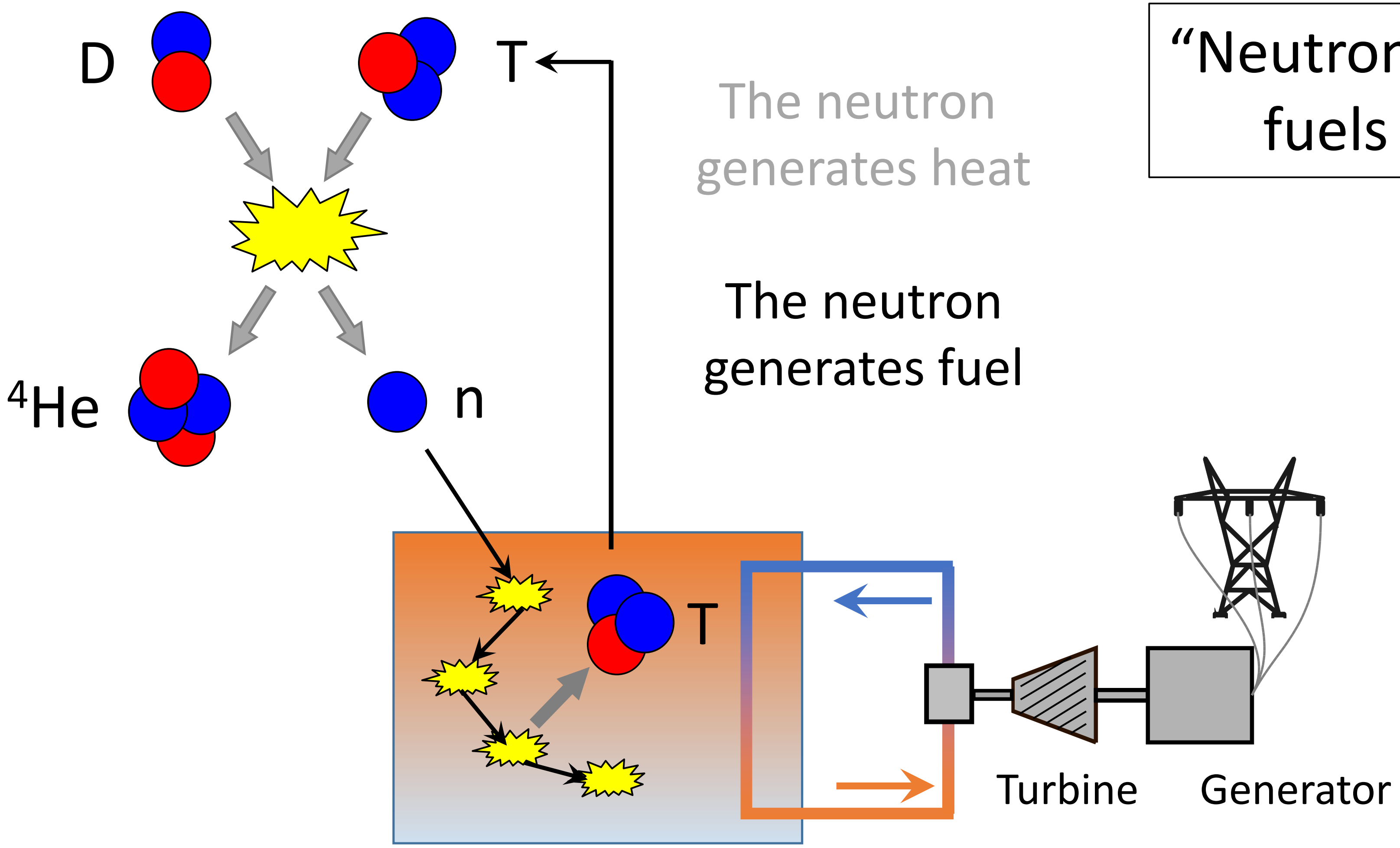
“Neutronic” fuels



The neutron generates heat

The neutron generates fuel

Heat conversion and fuel generation

The exhaust products of the viable fusion fuels determine how fusion energy is converted to electricity.

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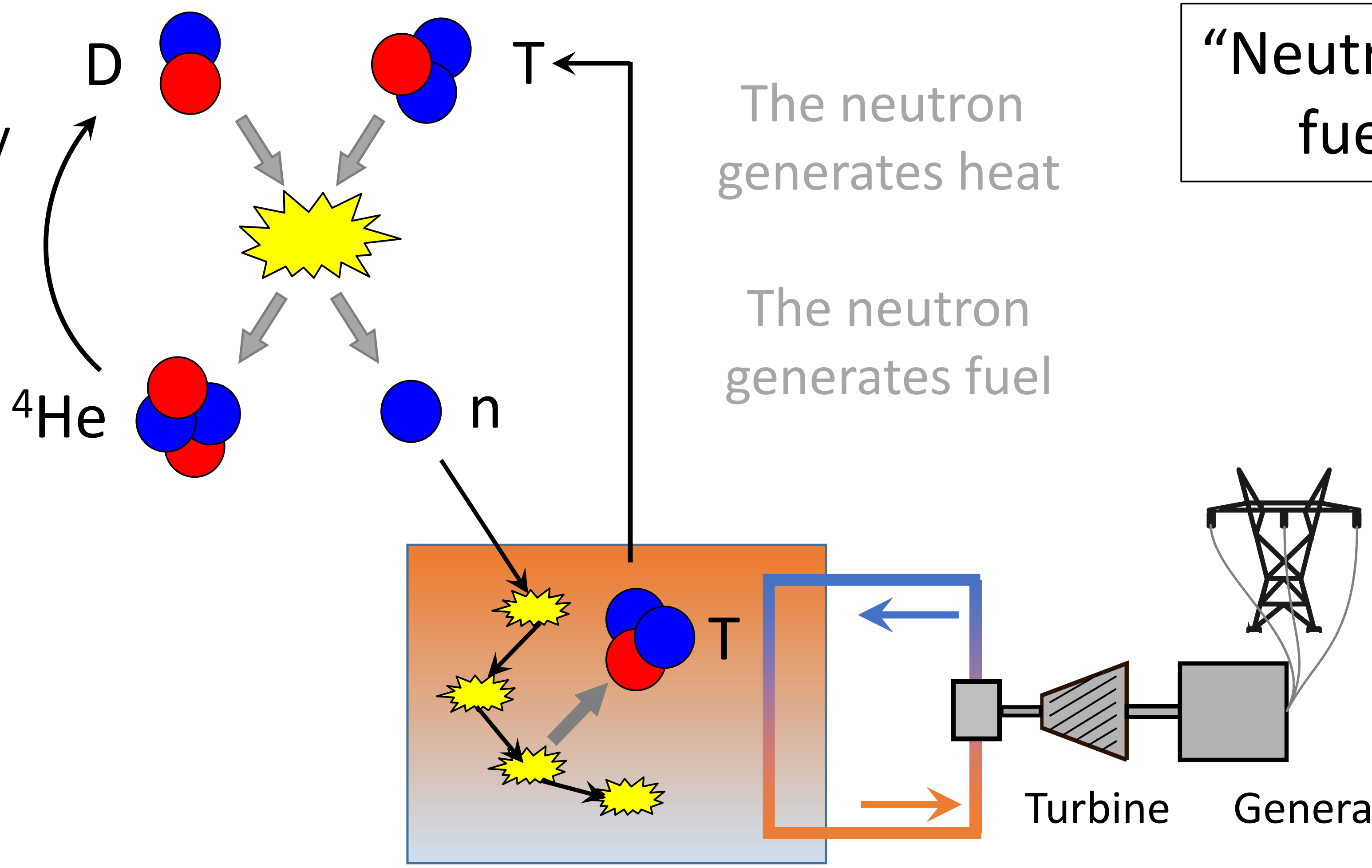
“Neutronic” fuels

Helium nuclei transfer energy to D and T

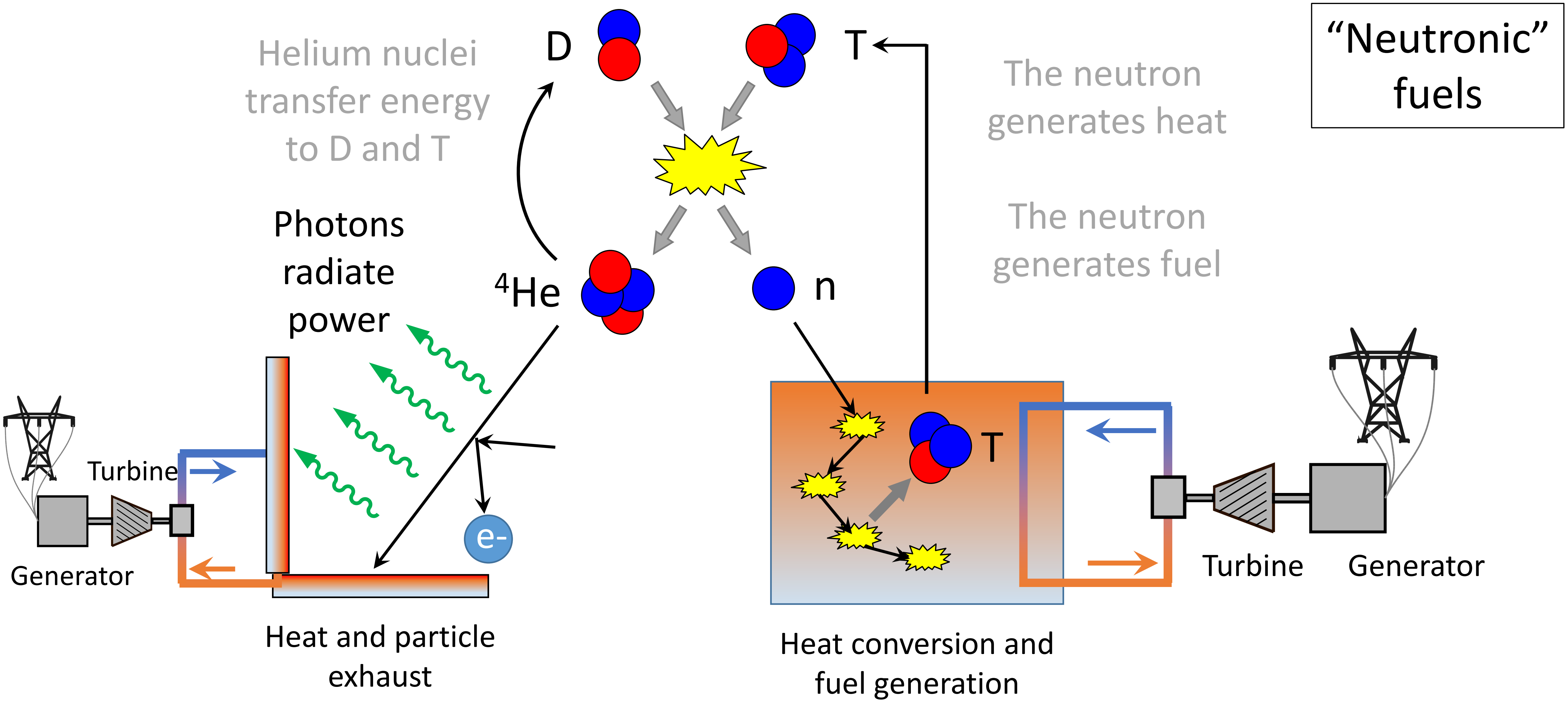


The neutron generates heat

The neutron generates fuel

Heat conversion and fuel generation

The exhaust products of the viable fusion fuels determine how fusion energy is converted to electricity.



The exhaust products of the viable fusion fuels determine how fusion energy is converted to electricity.

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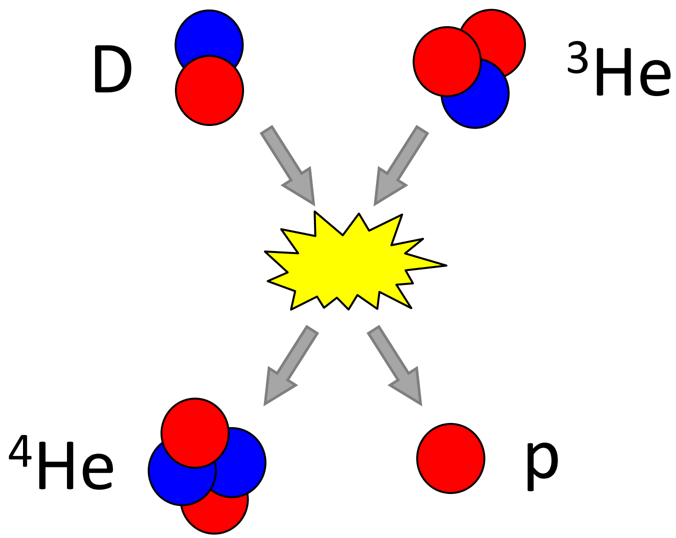

"Aneutronic" fuels

The exhaust products of the viable fusion fuels determine how fusion energy is converted to electricity.

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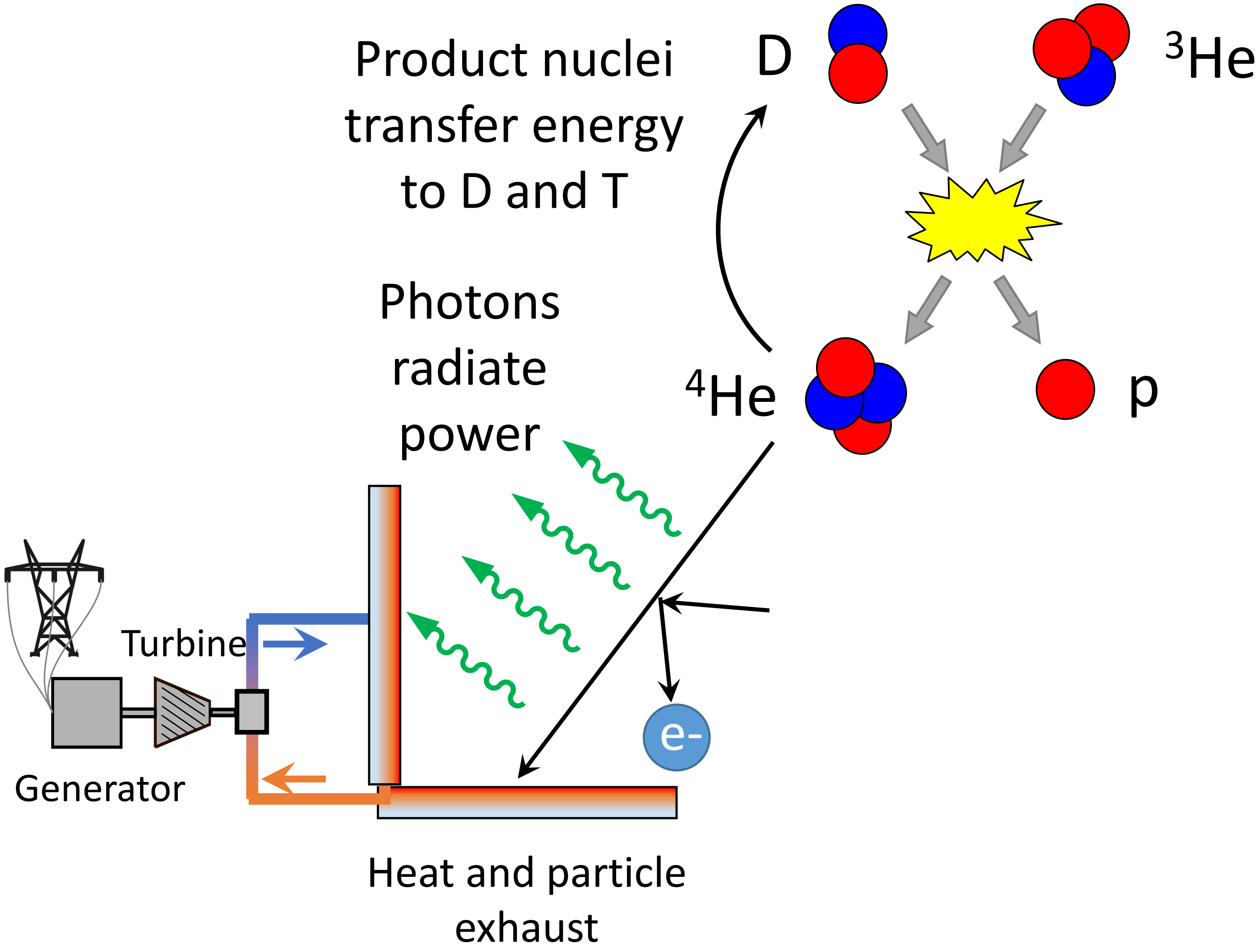
“Aneutronic” fuels



The exhaust products of the viable fusion fuels determine how fusion energy is converted to electricity.

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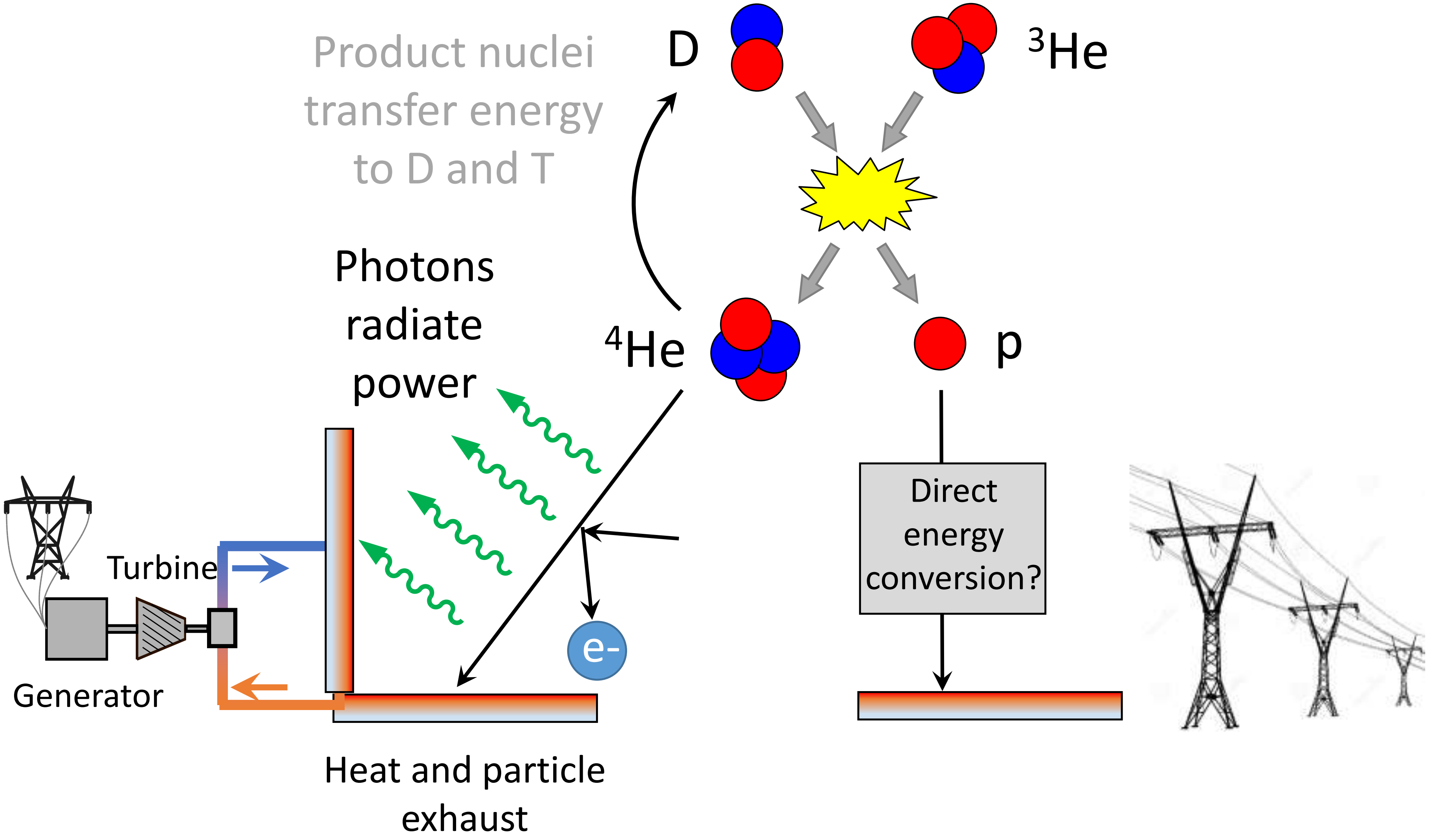
"Aneutronic" fuels



Q1: What are the viable fusion fuels and how do they affect the approach?

Rule 1

Fuel choice fundamentally sets the
difficulty of any approach to fusion energy

D-T fuel is the easiest by far.
D-D and D-^{3}He increasingly difficulty.
p-^{11}B possibly infeasible; other fuels are not viable.

Questions you should ask:

"What fusion fuel are they using? Do they acknowledge difficulties?"
"How do they propose conversion to electricity?"
"How mature and demonstrated is this technology?"

Part 1 : Developing "The Rules" for assessing fusion energy concepts

- Q1: What are the viable fusion fuels and how do they affect the approach?
- Q2: What are the physical conditions required to achieve net fusion energy?
- Q3: What fusion energy approaches exist and how should they be evaluated?

Part 2 : MIT's accelerated pathway to demonstrate net fusion energy

The conditions for burning wood (net chemical energy release) are roughly analogous for burning a plasma (net fusion energy release)

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Wood density

Wood temperature

Energy confinement

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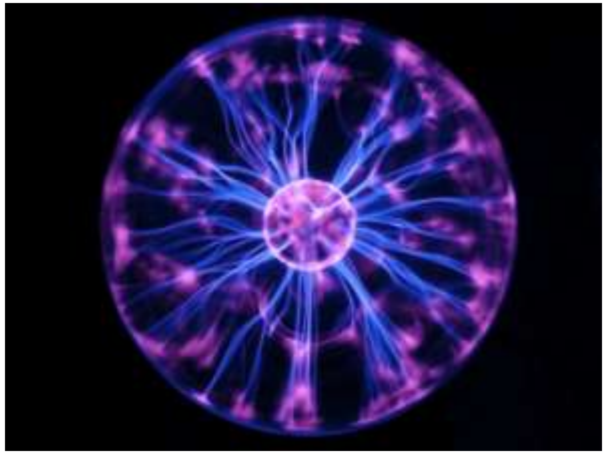
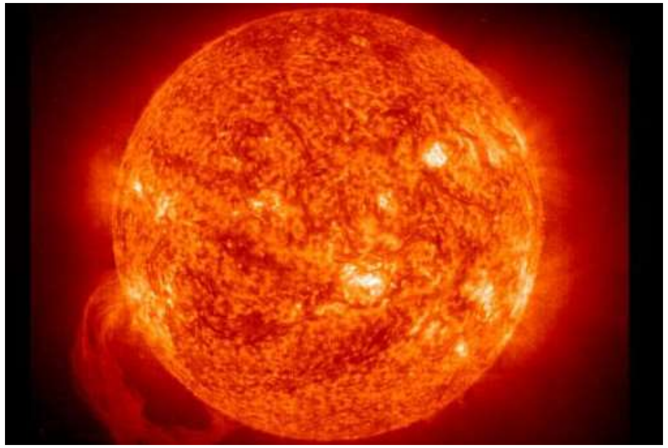
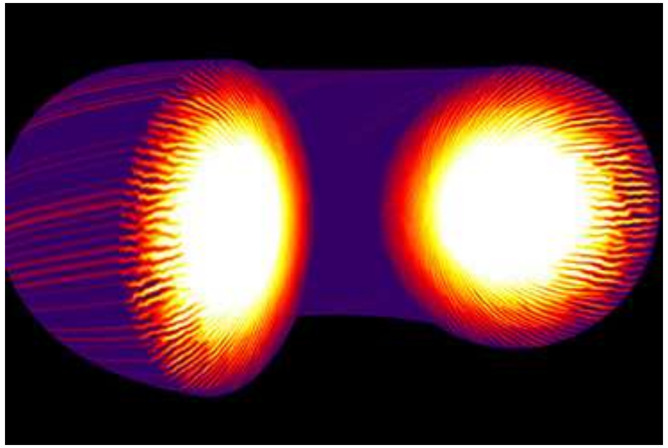


Plasma density



Plasma temperature



Energy confinement

$$n \times T \times \tau_E$$

The three things required for fusion energy … known since 1955!

Visualizing the Lawson criterion is a powerful way to assess how close a particular fusion concept is to achieving the necessary conditions

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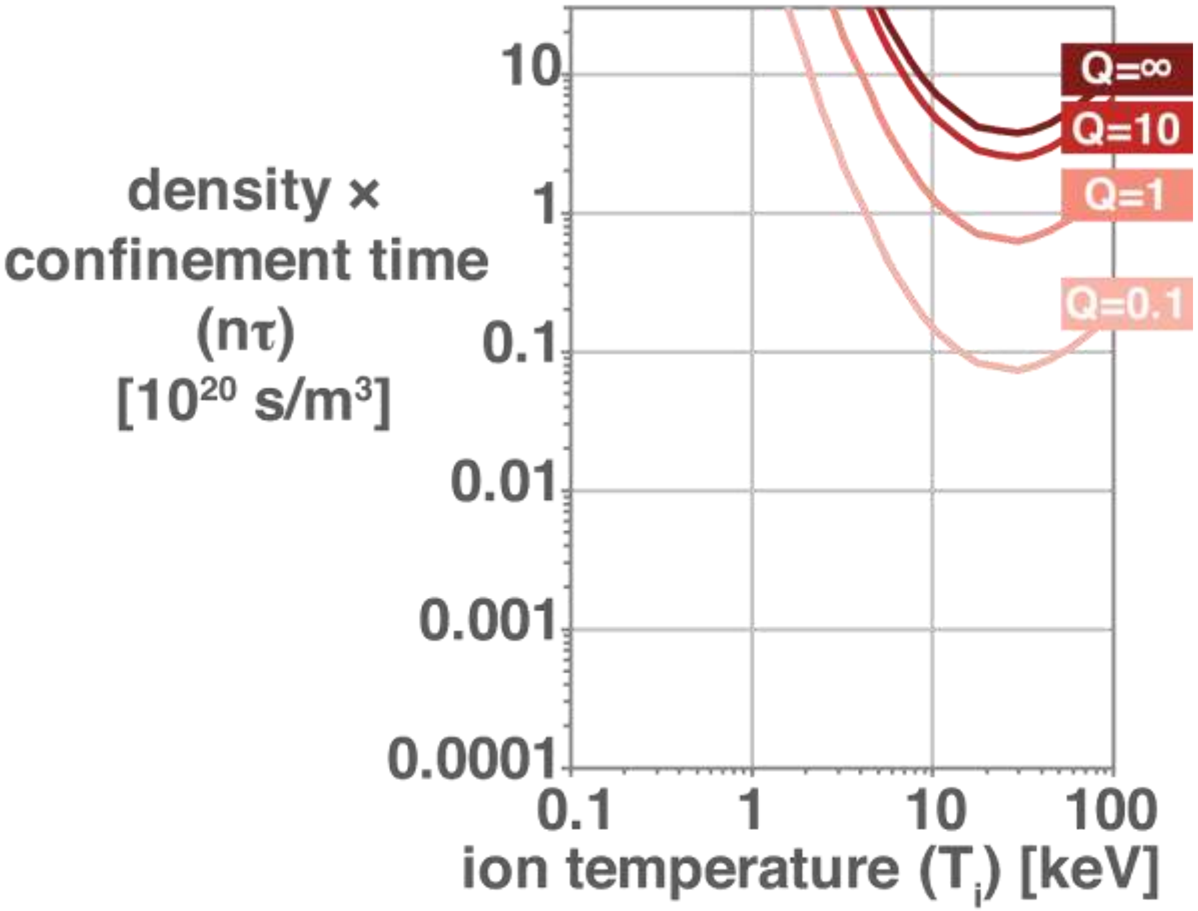

$$Q = \frac{Fusion\ energy\ output}{Energy\ input}$$

Visualizing the Lawson criterion is a powerful way to assess how close a particular fusion concept is to achieving the necessary conditions

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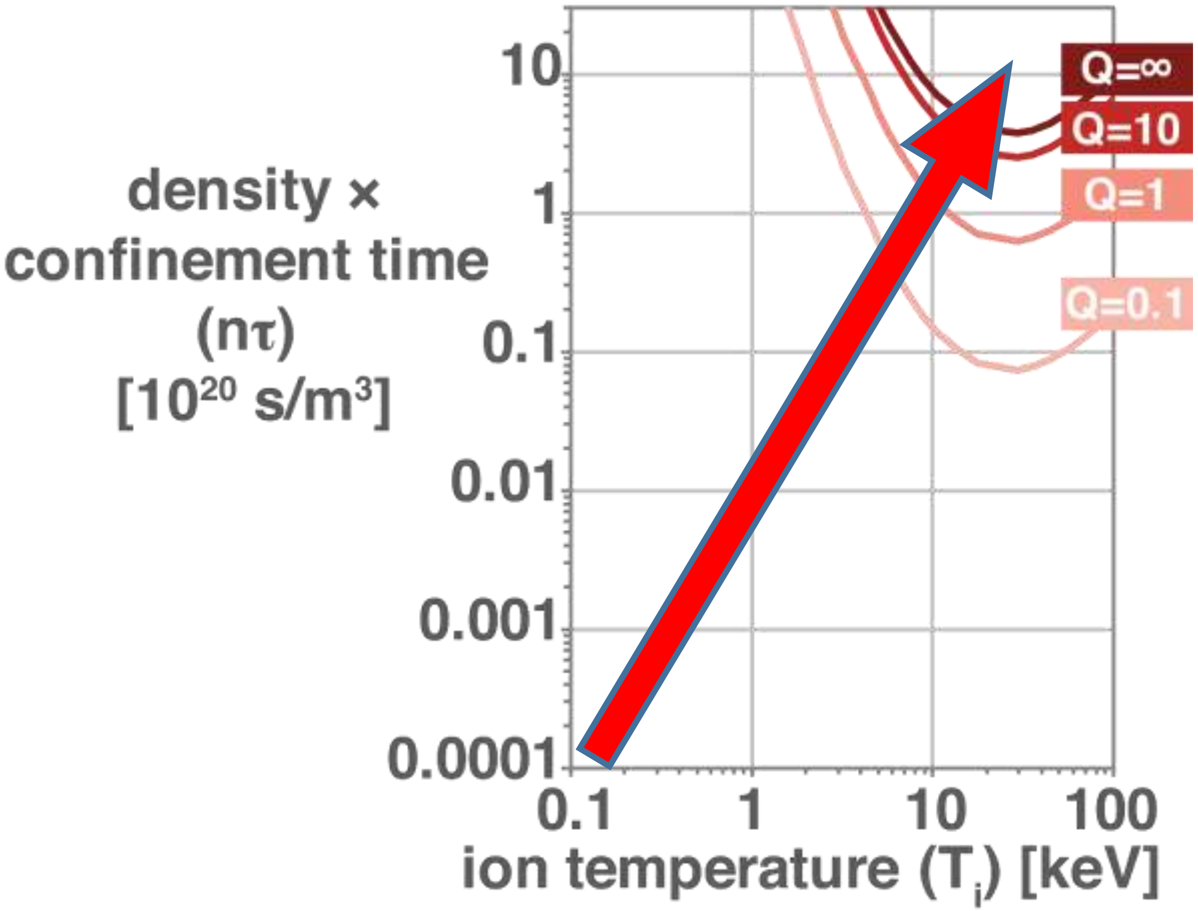

Moving into the upper-right corner has been the primary goal of fusion energy research for almost 60 years …

Visualizing the Lawson criterion is a powerful way to assess how close a particular fusion concept is to achieving the necessary conditions

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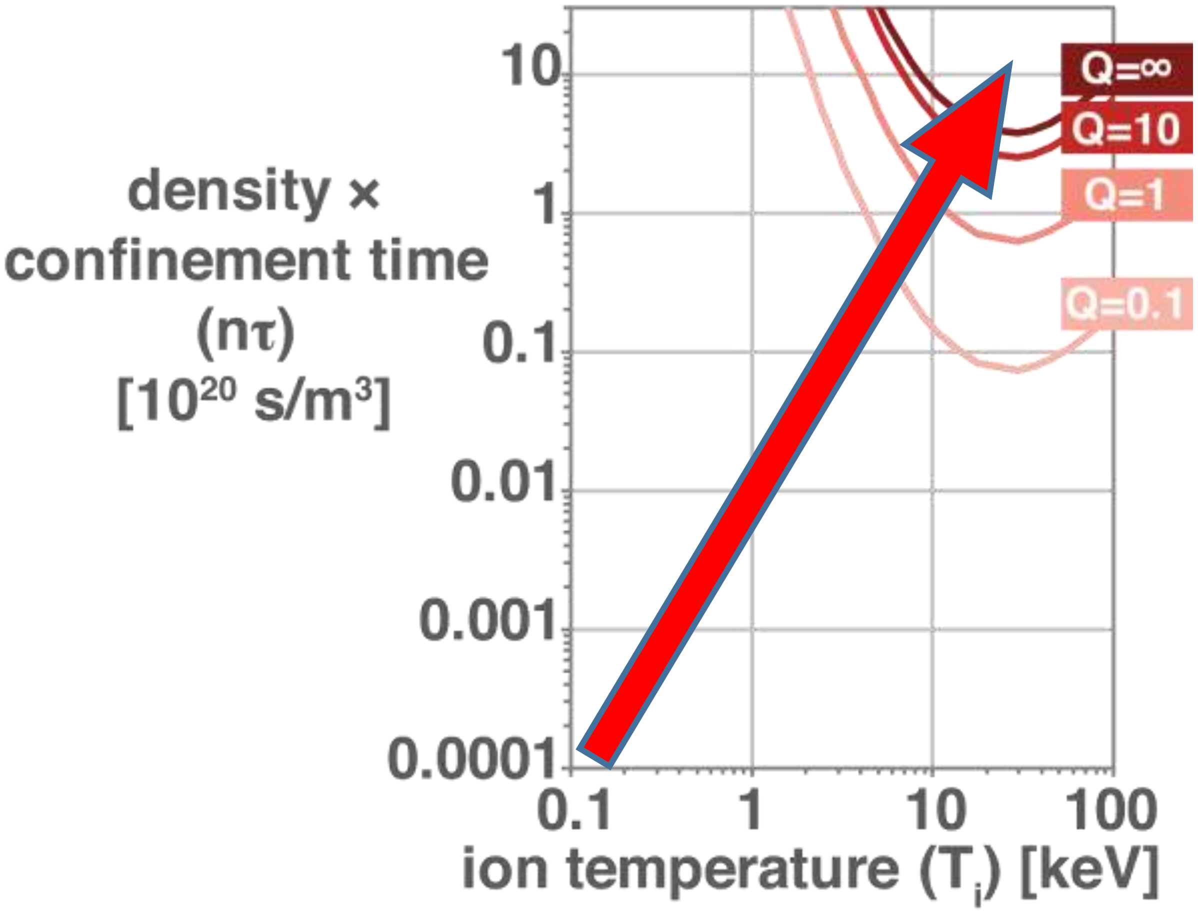
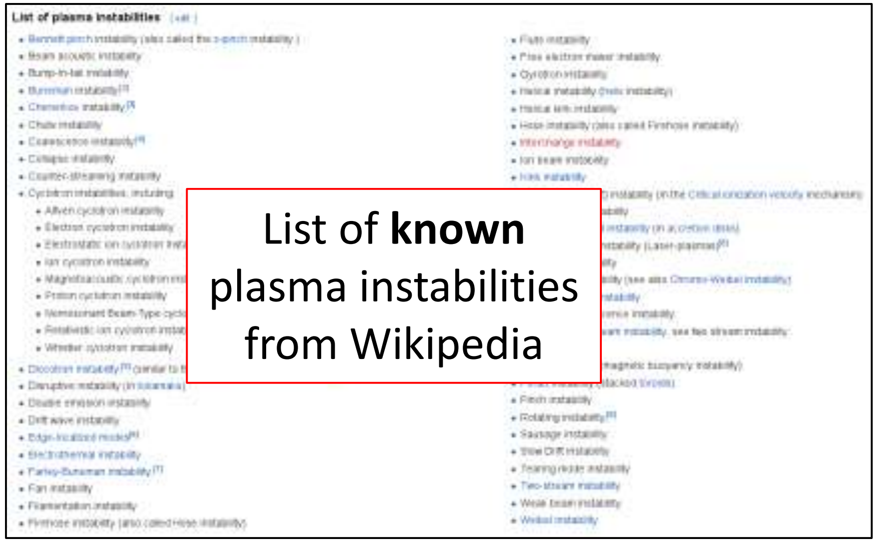
Be **very** wary of extrapolation in this space …



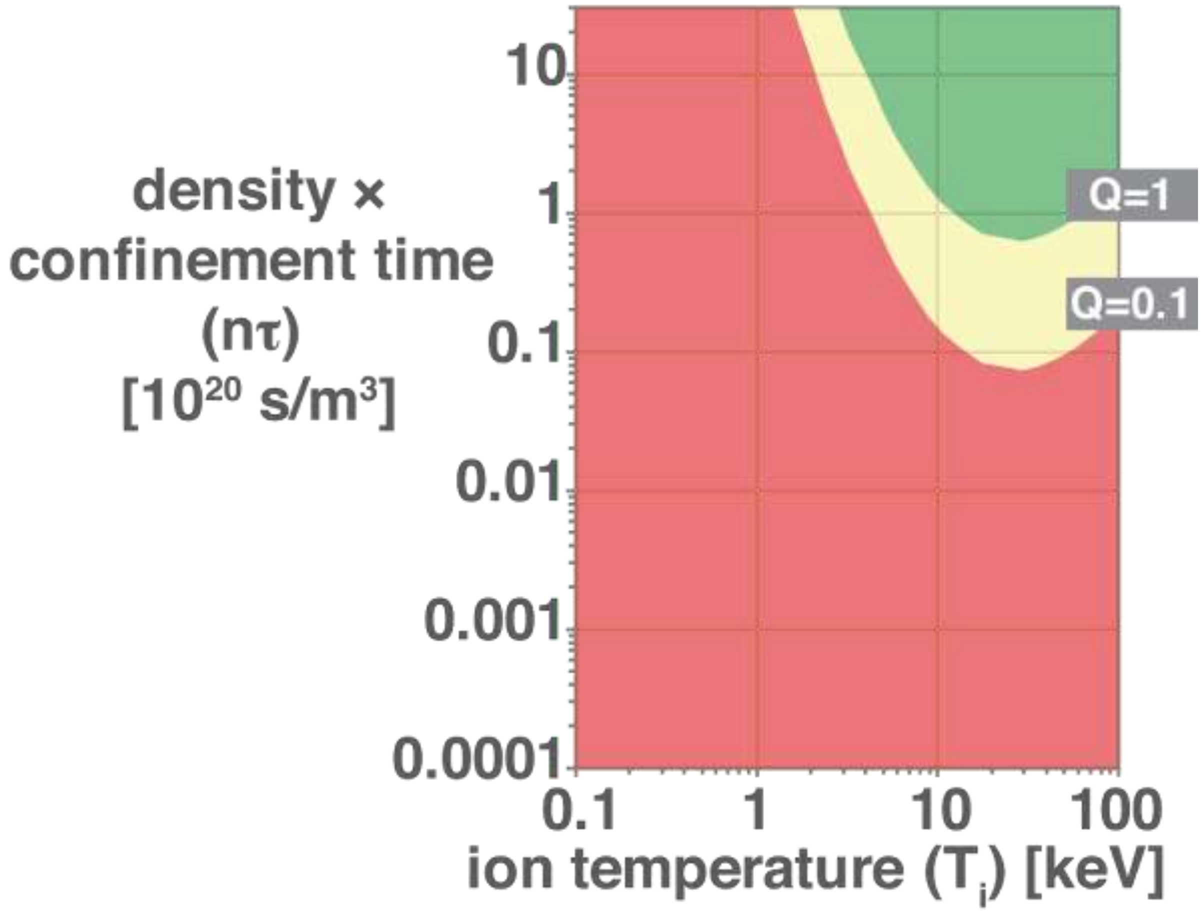
Moving into the upper-right corner has been the primary goal of fusion energy research for almost 60 years …

This turns out to be enormously difficult

- Moving orders of magnitude in dimensional, absolute parameters
- Unknown unknowns (plasma instabilities) wait to destroy your fusion energy dreams



List of **known** plasma instabilities from Wikipedia



What does this mean for fusion energy concepts?

Let’s make a simple analogy…

Visualizing the Lawson criterion is a powerful way to assess how close a particular fusion concept is to achieving the necessary conditions

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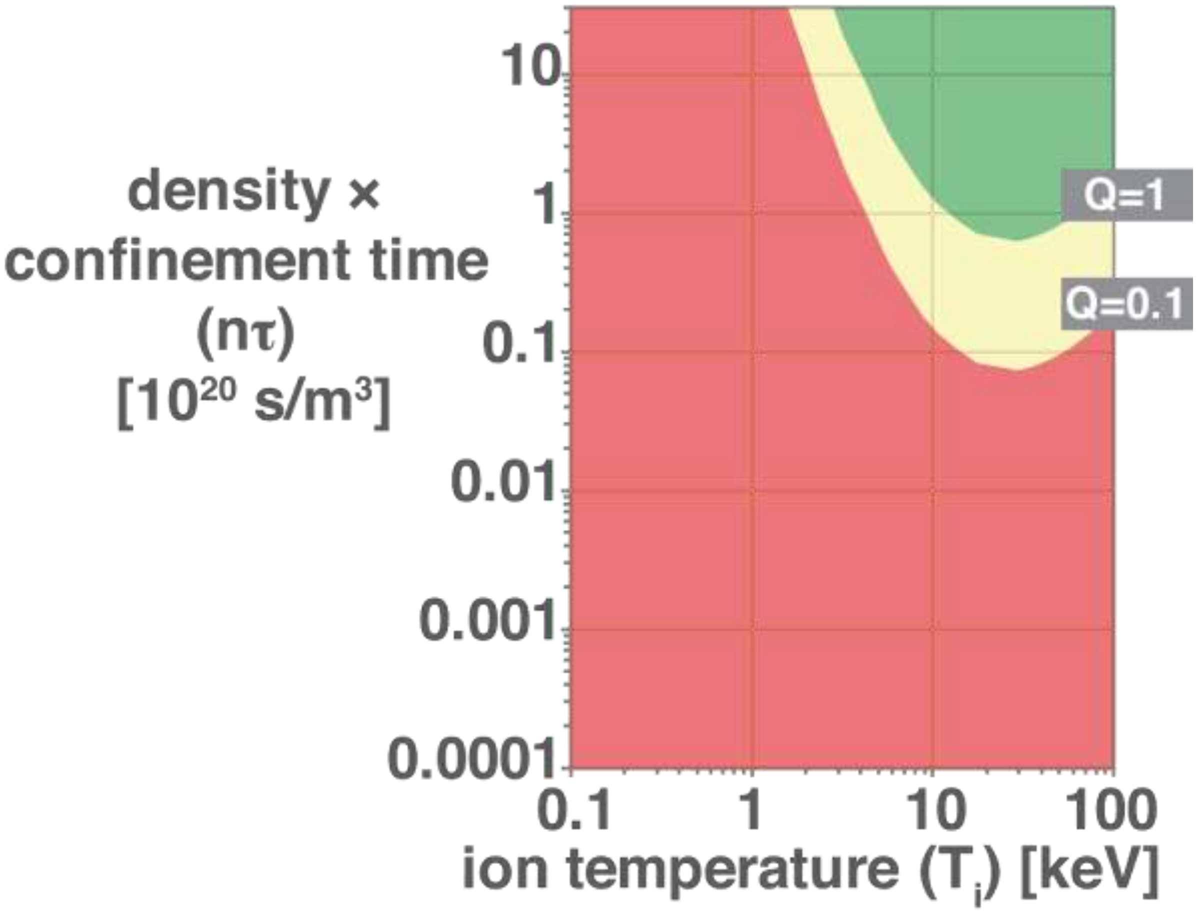

Fusion energy: The Ride!

Visualizing the Lawson criterion is a powerful way to assess how close a particular fusion concept is to achieving the necessary conditions

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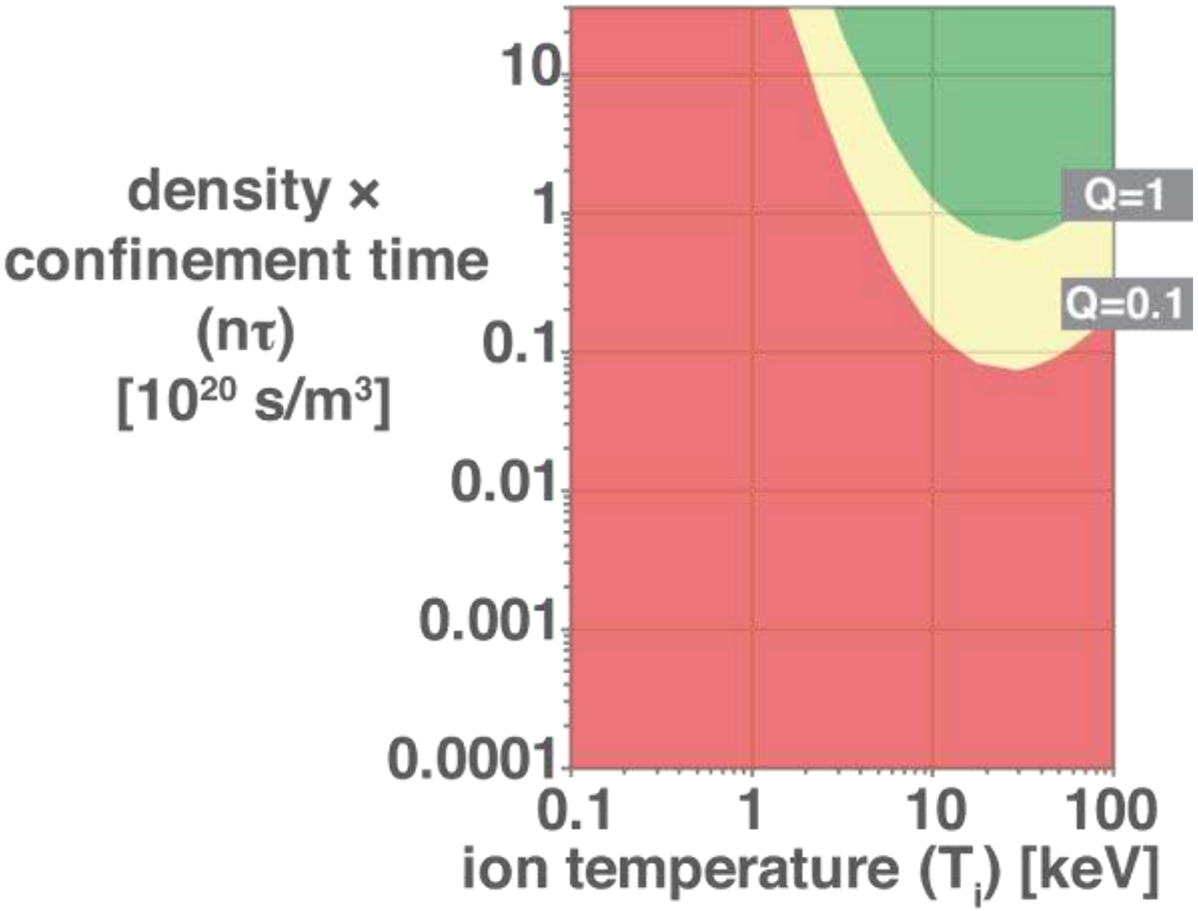
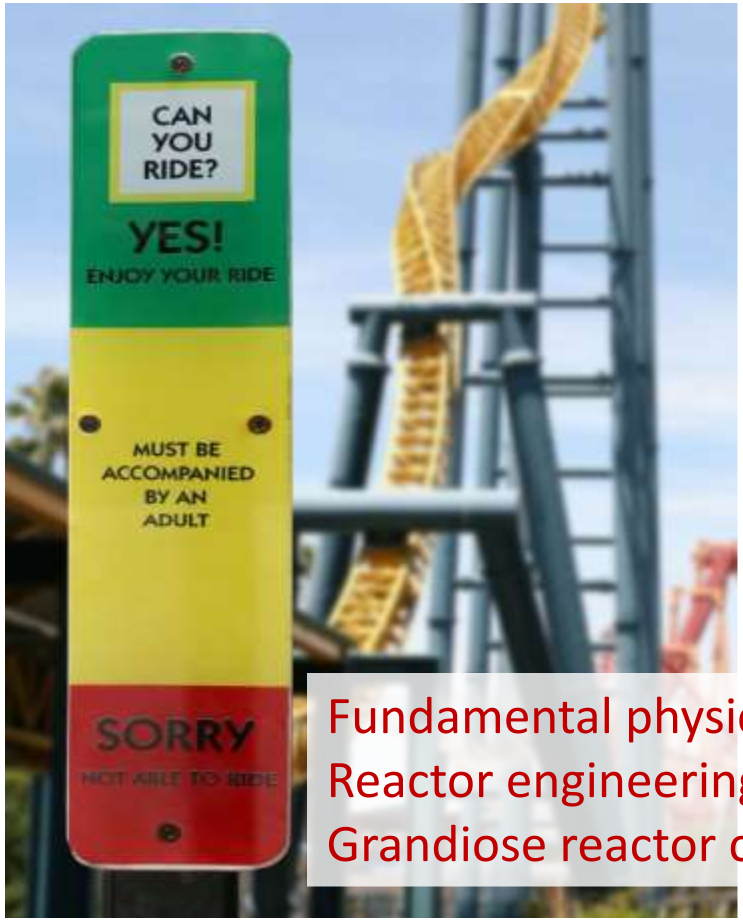
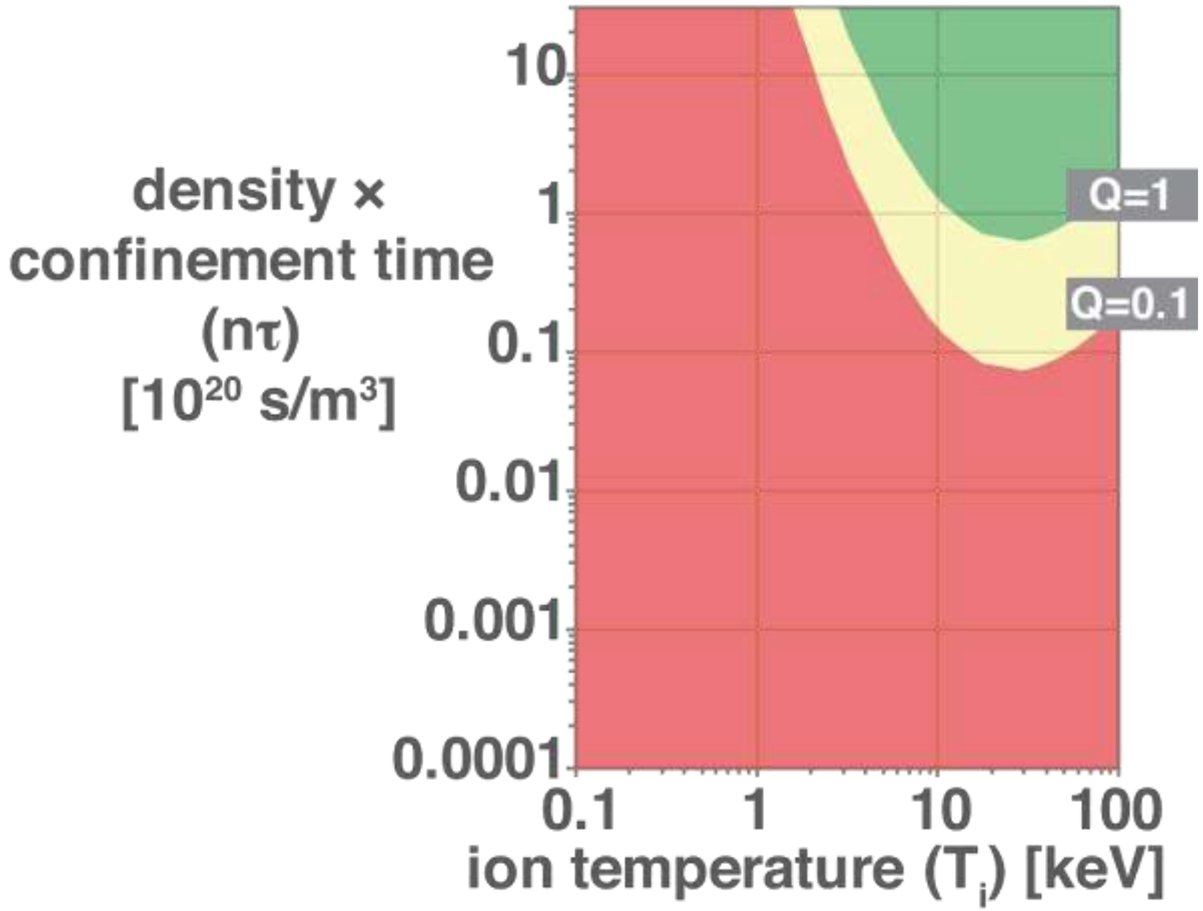




Fundamental physics is not yet viable
Reactor engineering is wasted effort
Grandiose reactor claims are exploitative

PSFC



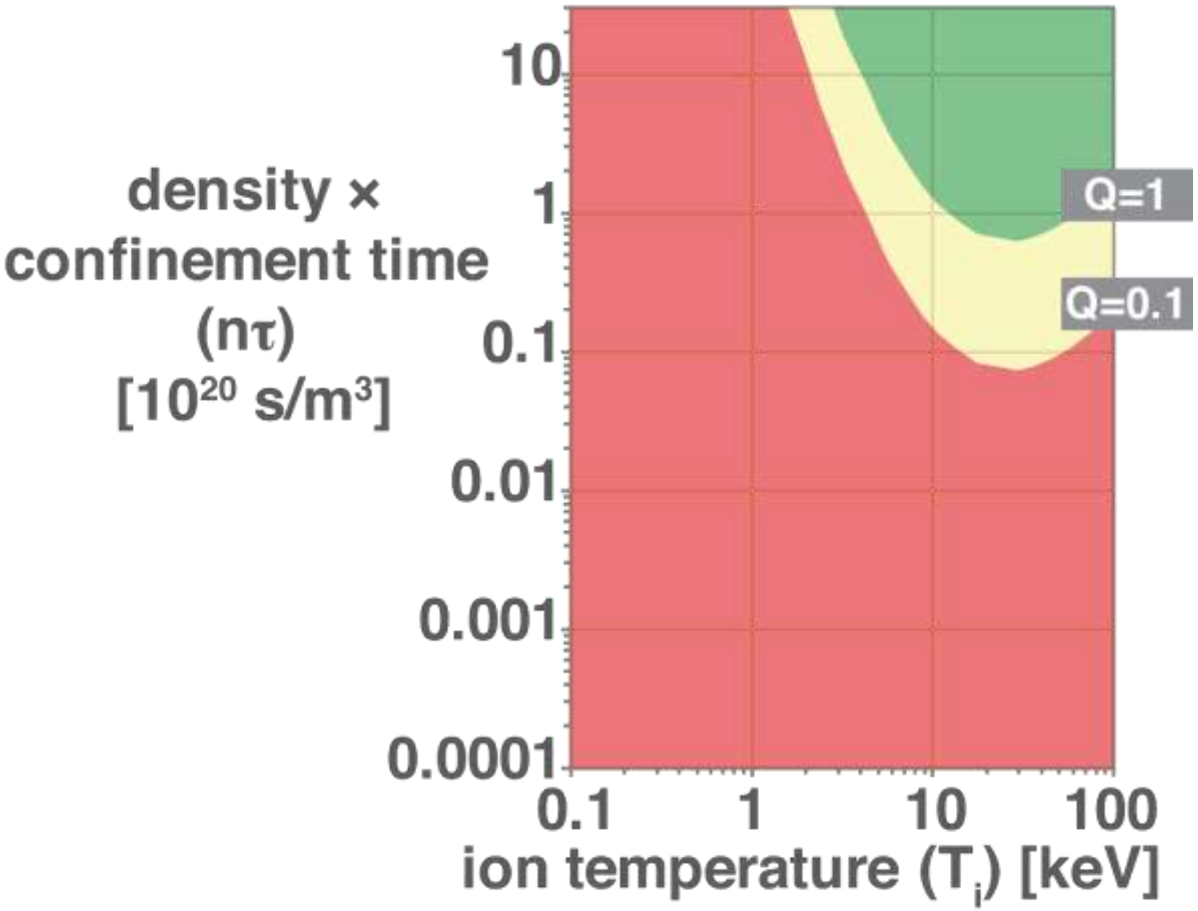
Physics is nearing full demonstration

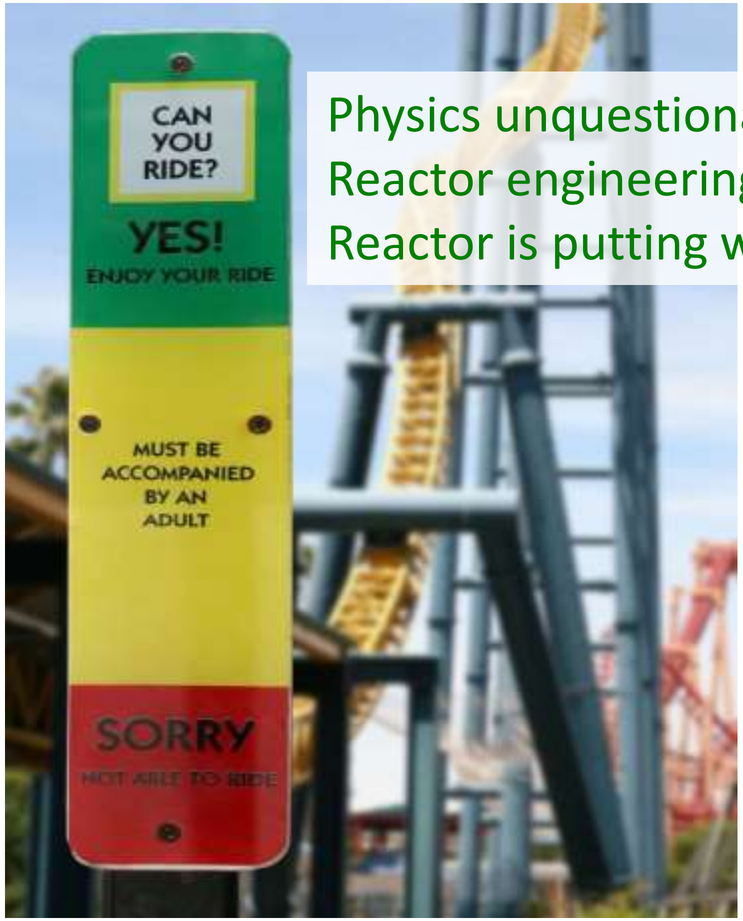
Reactor engineering seems justified

Reactor claims are reasonable

Visualizing the Lawson criterion is a powerful way to assess how close a particular fusion concept is to achieving the necessary conditions

PSFC





Physics unquestionably demonstrated
Reactor engineering should be mature
Reactor is putting watts on the grid

Q2: What are the physical conditions required to achieve net fusion energy?

Rule 2

Proximity to burning plasma conditions is the ultimate arbiter of the viability of any fusion energy approach.

T and $n\tau_E$ giving ~$Q \geq 0.1$ is ready for fusion energy.
T and $n\tau_E$ giving ~$Q \leq 0.1$ is a physics experiment.

Questions you should ask:

"What is the plasma pressure? The ion temperature? The confinement time?"
"What Q values (energy gain) are achieved on present machines?"
"Is the plasma magnetohydrodynamically (MHD) stable?"
"What problems with turbulence are they encountering?"

Part 1 : Developing "The Rules" for assessing fusion energy concepts

- Q1: What are the viable fusion fuels and how do they affect the approach?
- Q2: What are the physical conditions required to achieve net fusion energy?
- Q3: What fusion energy approaches exist and how should they be evaluated?

Part 2 : MIT's accelerated pathway to demonstrate net fusion energy

There are a surprisingly large number of ways to attempt fusion energy. This is a heavily abridged visualization!

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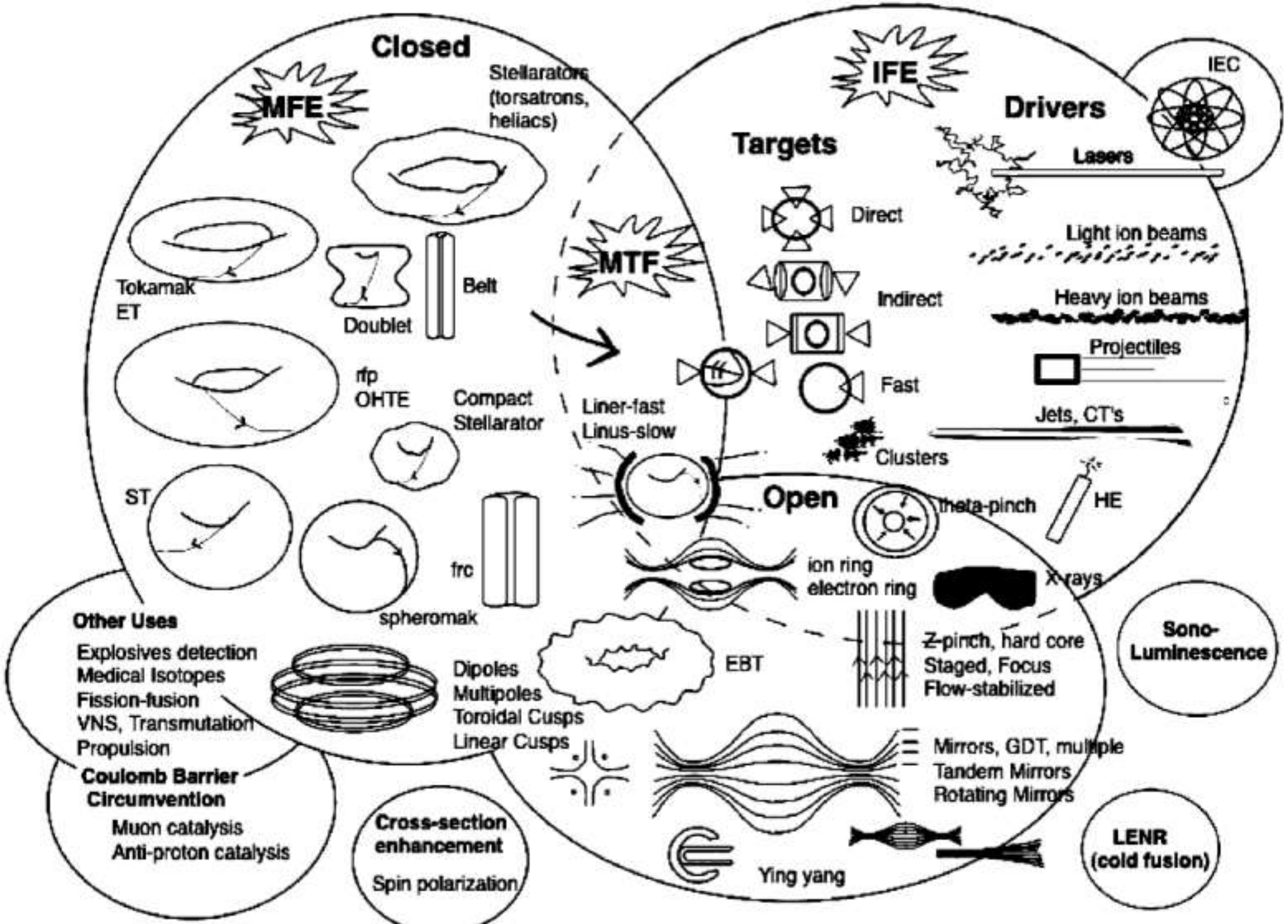

[1] S. Woodruff, *Journal of Fusion Energy*, **23** (2004) 27-40.

Cold fusion (alias: Low energy nuclear reactions or “LENR”) can be described by no known physical model and has never achieved verified power production

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Confinement basis

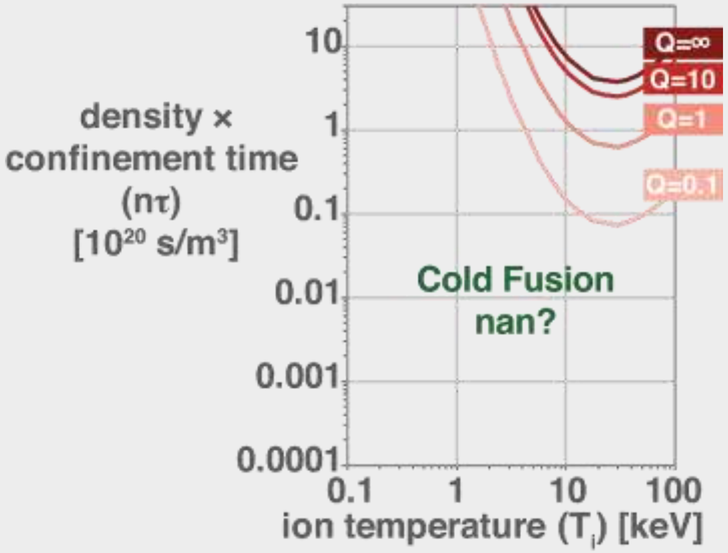
- Cold Fusion / LENR

Active experiments:

- Surprisingly numerous, “eCAT”

Key lessons learned:

- If it’s too good to be true, then it almost certainly is.



- Cold fusion purports to use some process to create fusion energy conditions at room temperature
  - First “discovered” by Pons and Fleischmann in 1989

- Proposed processes cannot be rectified with any known model of physics
  - Rapidly and continually debunked
  - Zero independent validation by critics
  - Initial Pons and Fleischmann debunking done by MIT


Boston Herald

MIT bombshell knocks fusion ‘breakthrough’ cold

- Considered a *pathological science*: research that continues in an enthusiastic minority long after scientific consensus establishes it as false

Gravitational force confines plasma and create the conditions necessary for sustained generation of fusion energy in the stars

Confinement basis

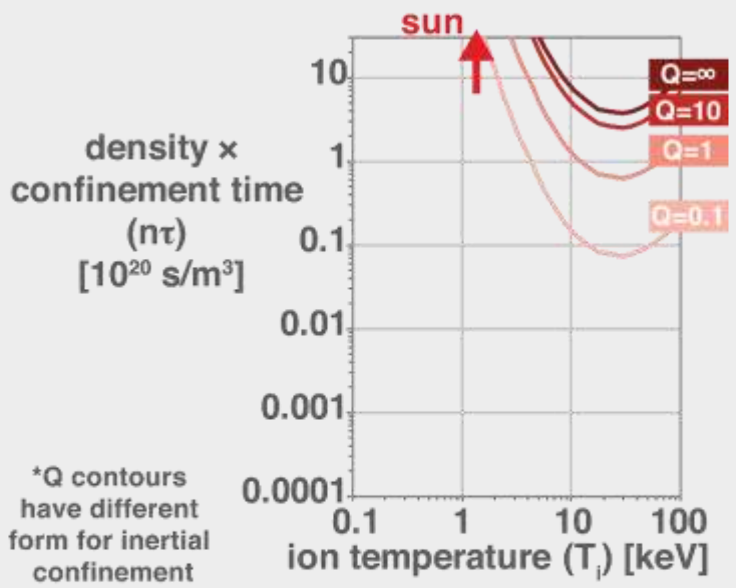
- Gravity

Active experiments

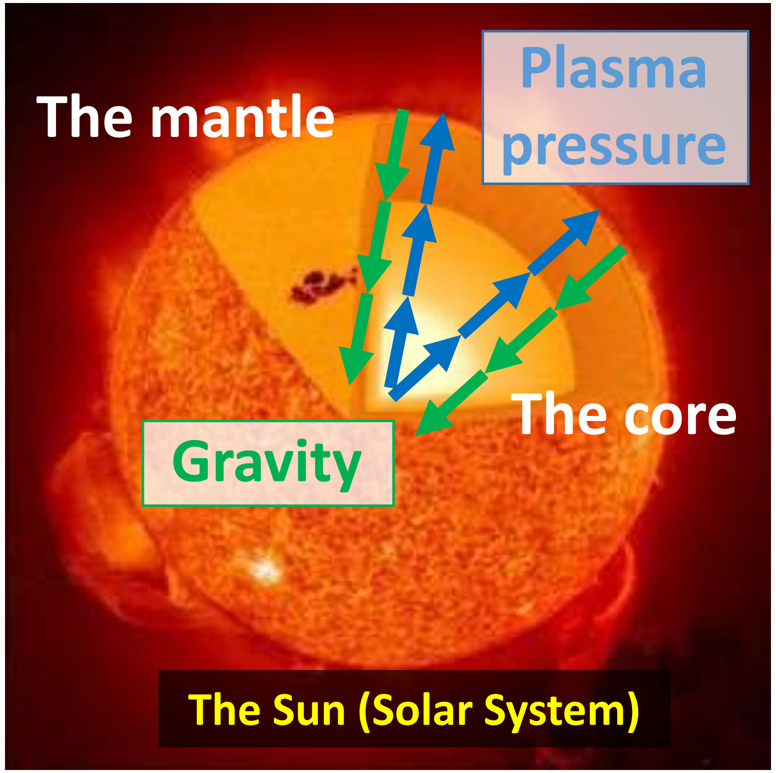
- See: The universe

Key lessons learned

- Conditions required for net energy fusion are allowed by this universe, but need different confinement mechanism



- Stars initially fuse hydrogen but progress to fusing heavier elements
- Energy release from fusion reactions generates **tiny** power densities but over **massive** volume:
  - 0.27 W/m^3 average power density (about your average compost pile)
  - ~10^{27} m^3 (absolute volume)
- Stars exist balance plasma pressure with gravity
  - Not likely to be replicated on Earth in the near term

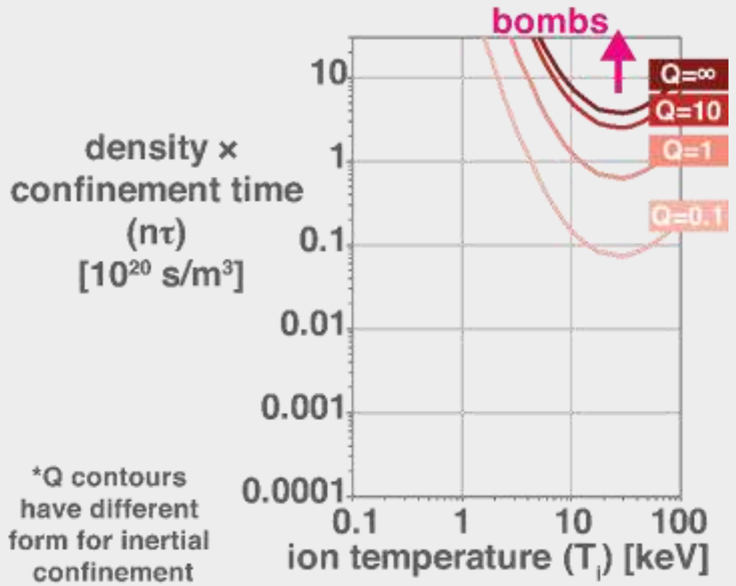


H-bombs create fusion initiated by fission bombs, but resulting blast is unacceptable and infeasible for energy production.

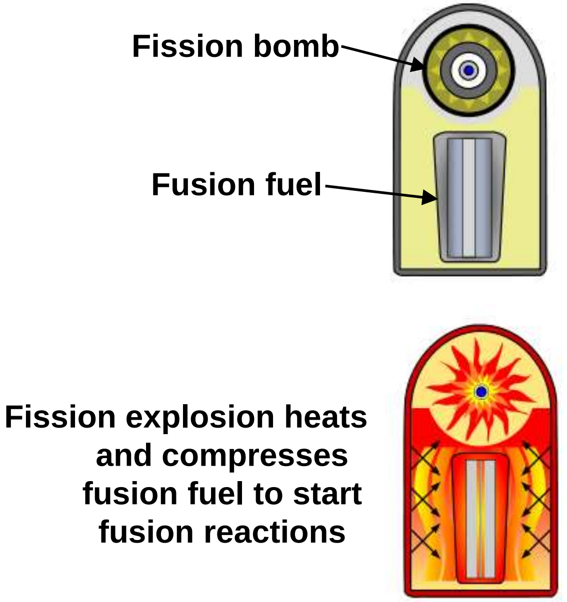
Confinement basis:
- Inertia with implosion driven by fission bomb

Active experiments:
- Weapon-industrial complex

Key lessons learned:
- To date, only successful fusion net gain on Earth but not great for energy…



- Fission bomb is ignited next to fusion fuel
  - Resulting X-rays rapidly heat and compress fuel to fusion conditions prior to destruction
  - Fusion boosts the fission explosion energy by 1000x
- Important to note: that fusion explosion *requires* fission explosion first
- Not a good power source!



Inertial confinement fusion (mini-bombs) has demonstrated impressive physics performance but has very unfavorable technological scaling to fusion energy.

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Confinement basis:
- Inertia with implosion driven by lasers

Active experiments:
- NIF,Omega (US), Laser Mégajoule (FR)

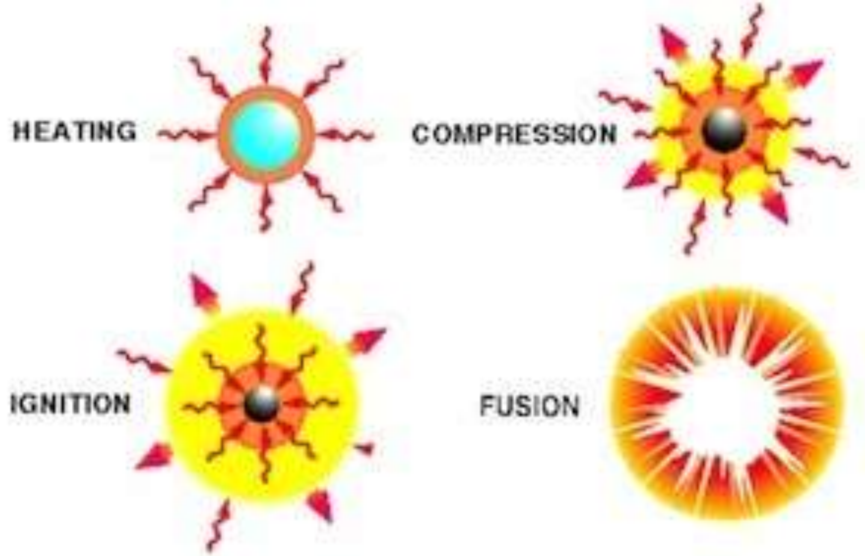
Key lessons learned:
- Capable of high performance but at very low rep rate and gain

Lawson criterion has different form for inertial confinement. Apples-to-apples comparison to magnetic confinement through Q for NIF:

$$Q = \frac{E_{\text{fusion}}}{E_{\text{driver-on-target}}} = \frac{17\text{ kJ}}{150\text{ kJ}} \approx 0.1$$

Hurricane, O. A., et al. *Nature* 506.7488 (2014): 343-348.

- Instead of using a bomb, use something else that is powerful and fast
    - Lasers: NIF, achieved near-breakeven
- Gives insight into how bombs work which is the primary purpose of the R&D
- Impressive performance but scaling to reactor looks difficult:
    - *Maintenance:* Significant machine components destroyed each implosion
    - *Rep rate:* present ~1/day (max); need ~1/s (need 100 000 scale-up)
    - *Efficiency:* 0.7% of NIF wall plug power makes it to the fusion fuel target



National Ignition Facility (LLNL)

Particle accelerators can easily achieve necessary conditions for fusion, but high Coulomb cross section compared to fusion cross section leads to tiny gain .

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Confinement basis:

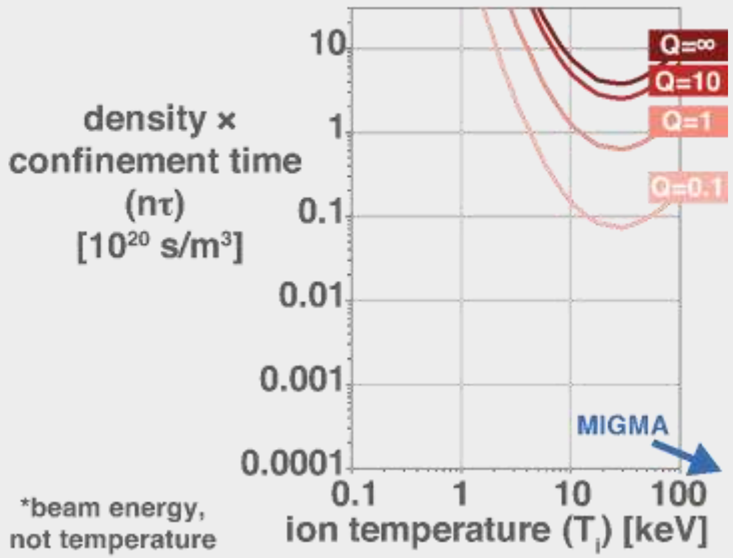
- Accelerating with electric fields

Active experiments:

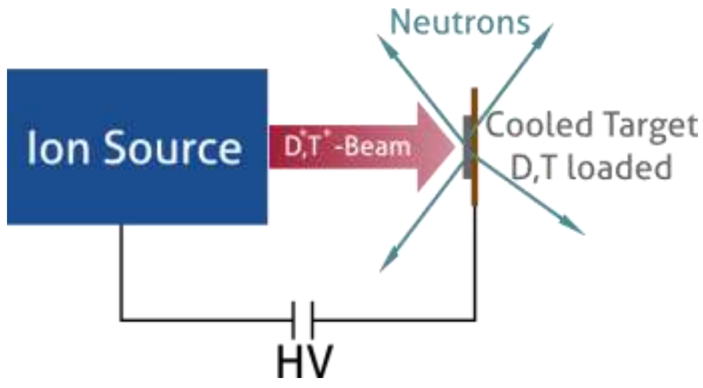
- Any accelerator with E ≥ 10 keV

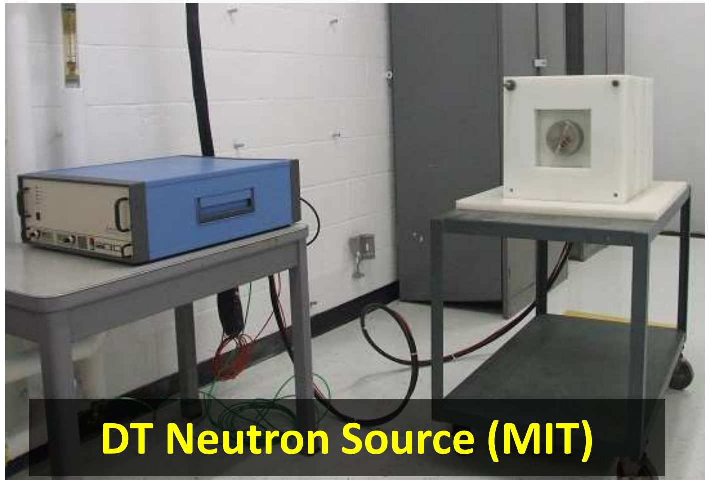
Key lessons learned:

- Coulomb collisions and instabilities reduce gain to unacceptable levels



- Fire beam of high energy particles into other particles
  - Easy to build a compact 100 keV beam
  - Can fuse anything from standard DT fuel (neutron source) to heavy ions (RHIC) depending on beam energy
- But…Coulomb cross section is ~100,000x too large
  - Beam ions slows down before fusion dominates
  - Beam requires more energy than it makes from fusion
- Good for neutron source, but low gain precludes energy generation





Electrostatic potential wells (fusors) can be used to accelerate and confine ions, but several loss mechanisms limit plasma performance

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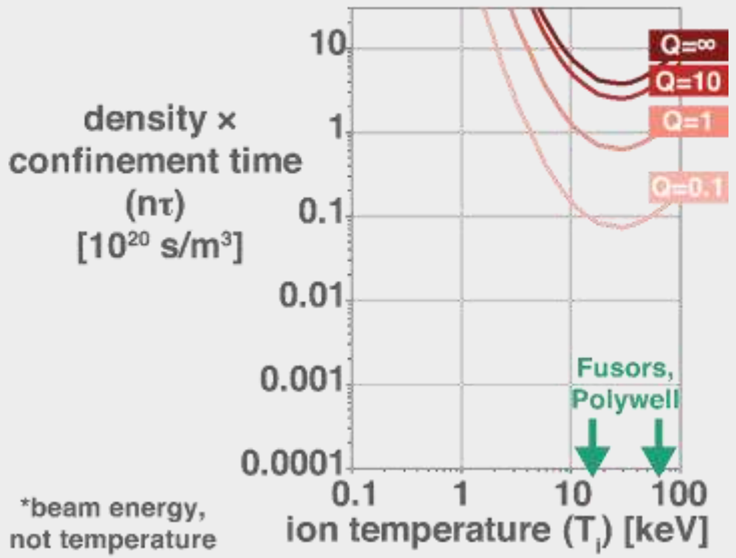
Confinement basis:
- Electric fields

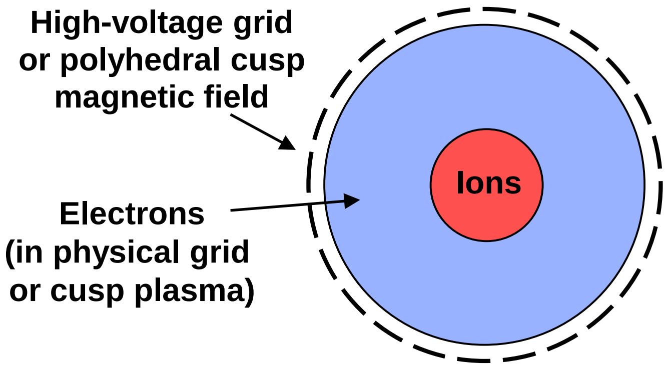
Active experiments:
- Hobbyists, university students

Key lessons learned:
- Simple devices, good for teaching tools but too many loss mechanisms for net power production



- A spherical ion accelerator with a potential well to collide ions against each other in the center
  - Physical high-voltage grid or a "virtual cathode" made of electrons
- Multiple mechanisms slow or eject the ions before *enough* fusion happens for net gain[1]
  - Coulomb collisions
  - Particle losses
  - Conduction losses
  - Bremsstrahlung
- While orders of magnitude from energy gain, can be effective simple neutron sources

[1] Rider, Todd H. "A general critique of inertial-electrostatic confinement fusion systems." *Physics of Plasmas (1994-present)* 2.6 (1995): 1853-1872.



Plasma in a fusor (hobbyist's garage)

<u>Magnetic mirrors</u> use a magnetic field to confine plasma in 2 dimensions and then unsuccessfully try to plug the losses along the magnetic field.

Confinement basis:

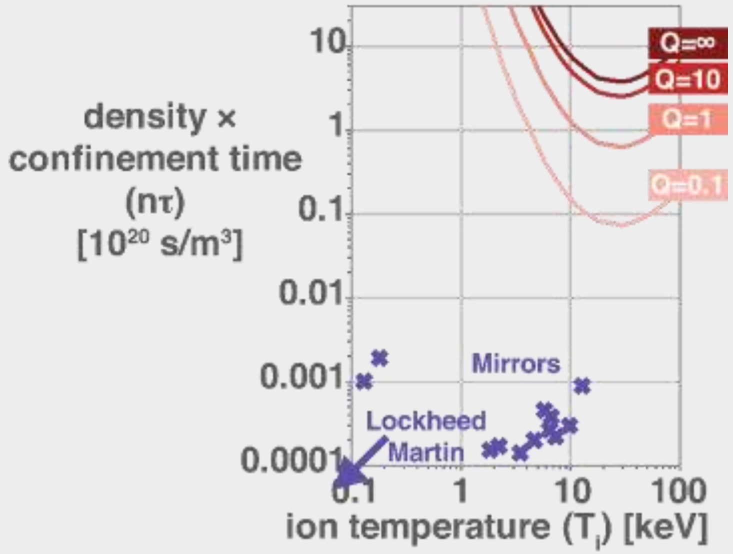
- Magnetic fields (crimped)

Active experiments:

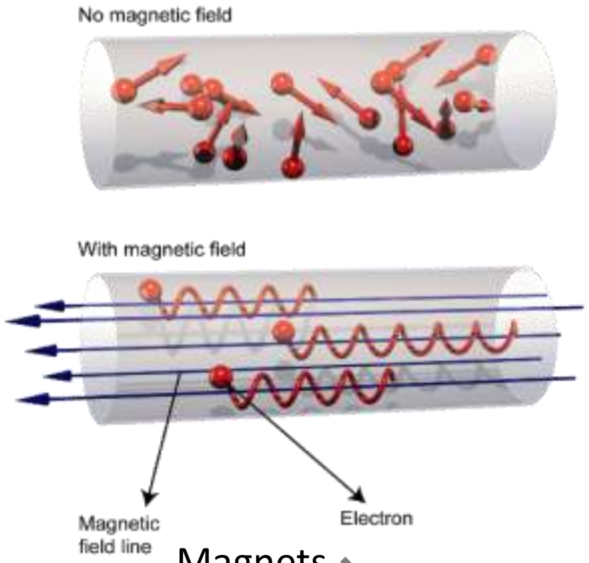
- Gamma-T (Japan), Gas Dynamic Trap (Russia), Lockheed Martin Co.

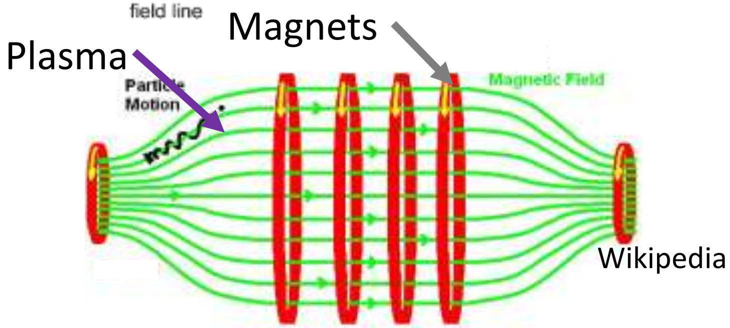
Key lessons learned:

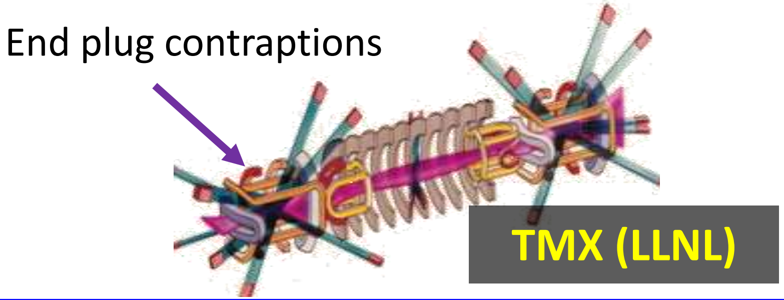
- Any open field lines lead to unacceptable losses



- Charged particles spiral around magnetic field lines
  - But confinement is only in 2D
  - Some particles always leak out the ends
- Many different configurations tried to plug the ends of the "mirror"
  - Large $1B-class experiments
  - Losses always dominate fusion unless the mirror is very long
- Conclusion: A net-energy device is unrealizably long (~km) still a good fusion neutron source







<u>Pinches or magnetized targets</u> use magnetic fields to rapidly compress the plasma before it leaks energy, but this creates instabilities.

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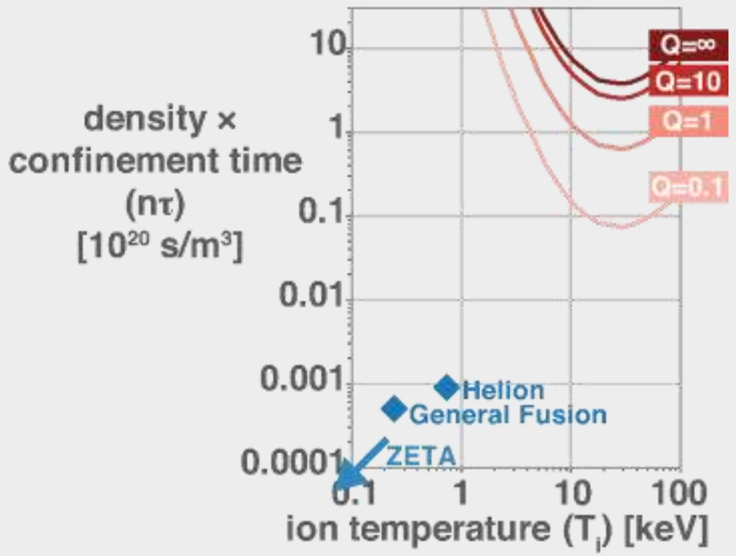
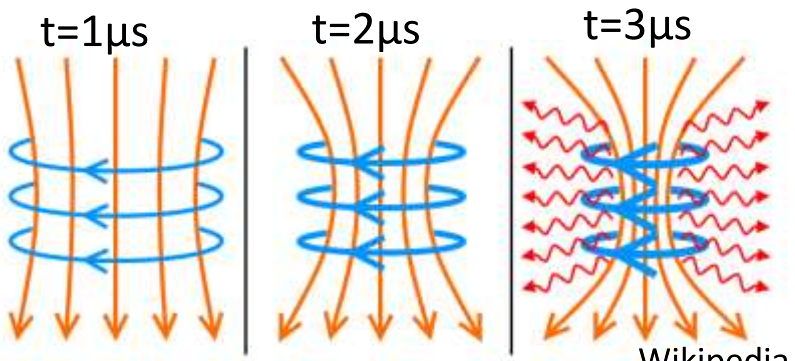
Confinement basis:
- Magnetic fields (squeezed)

Active experiments:
- Z-machine (SNL), Dense Plasma Focus (LLNL), ZaP (U. Wash), LPP co., General Fusion Co., Helion Co.

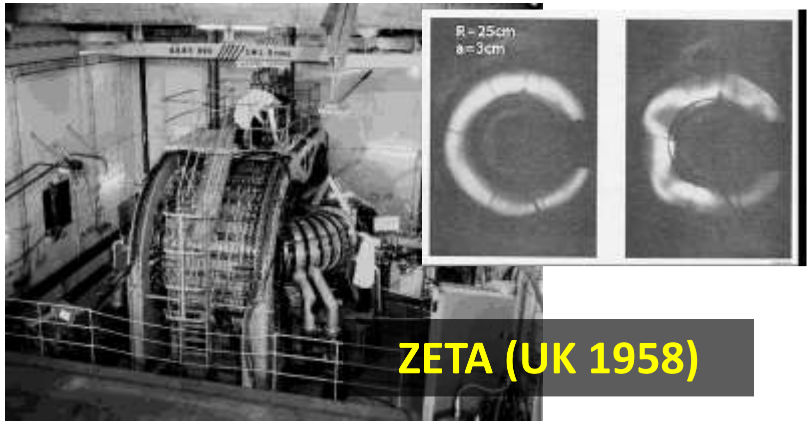
Key lessons learned:
- Instabilities are critically important



- Very quickly compress the plasma and heat it by rapidly changing magnetic field
- Many different configurations have been tried at many different scales
  - Requires large pulsed power systems
  - Often with sacrificial conductors surrounding plasma
- Large instabilities and plasma cooling occur before net-energy conditions are reached
  - Useful as a high-power X-ray or neutron source or particle accelerator



Wikipedia



A torus of mirrors or cusps eliminates end losses by turning the system onto itself but with the toroidal shape come new instabilities.

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Confinement basis:

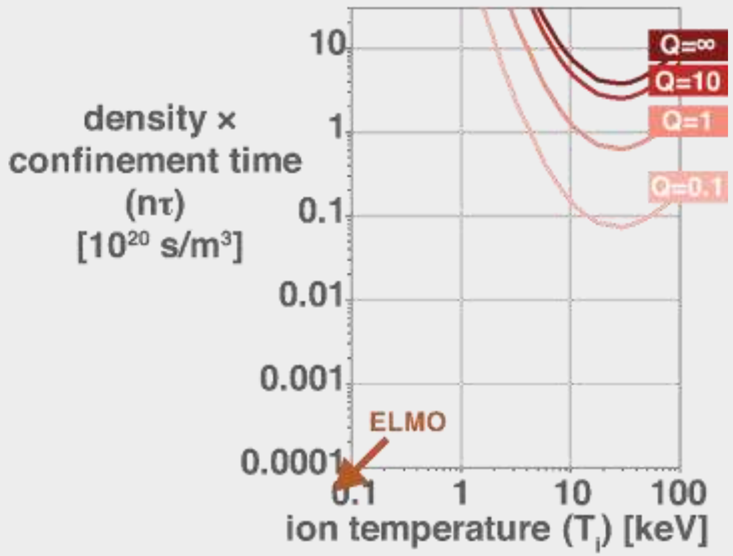
- Magnetic fields (bumpy)

Active experiments:

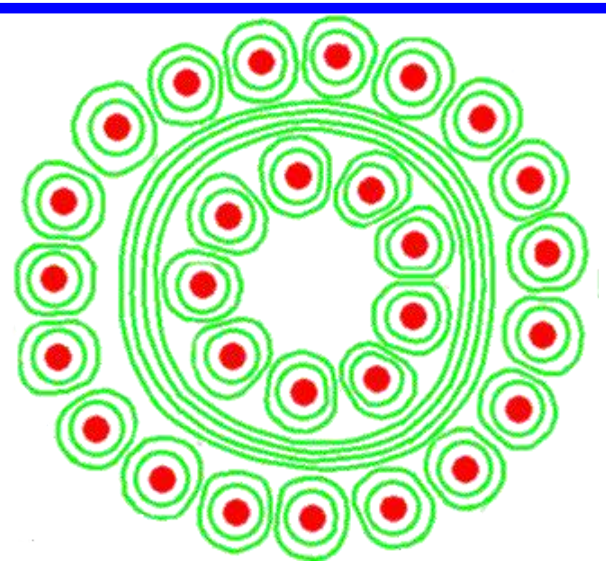
- None anymore

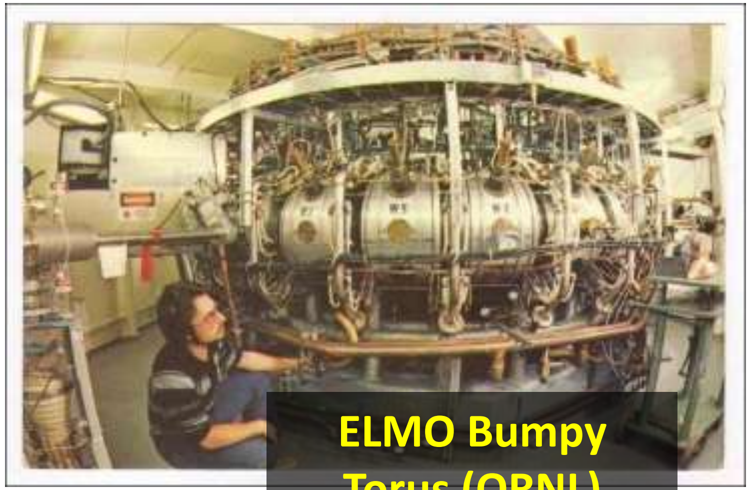
Key lessons learned:

- Symmetries are important



- Instead of plugging the mirror end losses, feed them into another mirror
  - Ad infinitum = A torus
- Tried with many geometry variations in the 1970s and 1980s in large programs
  - ORNL: ELMO bumpy torus
  - UC California: TORMAC
  - NASA: Bumpy torus
- But breaking the symmetry created additional instabilities in the plasma
  - Limited the temperatures and ruined confinement
  - Interesting plasma physics!





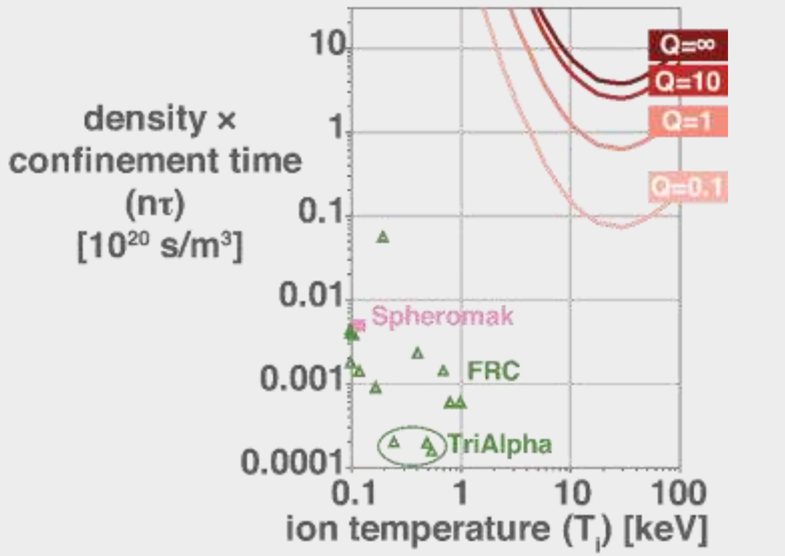
ELMO Bumpy Torus (ORNL)

Field-reverse configurations, spheromaks etc. use the plasma to create helical fields in the torus, increasing confinement at the expense of stability.

Confinement basis:
- Magnetic fields (self-twisted)

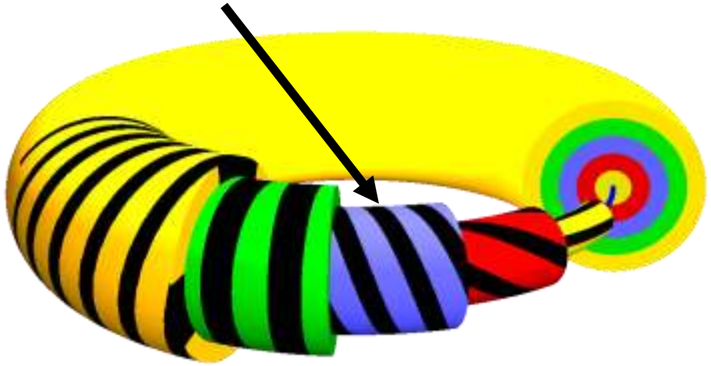
Active experiments:
- Tri-alpha Energy Co., RFX (EU), MST (U. Wisc.), Dynomak Co.

Key lessons learned:
- A helical magnetic field gives good confinement and sometimes stability, but relying on the plasma alone is difficult



- Instead of torus of many mirrors, make a torus with the magnetic field spiraling in a helix
  - Increases the stability
- Plasma can create these field shapes though "self-organization"
  - Transient effects limited to milliseconds
  - Studied widely over a long period
- Very rich plasma physics but very difficult to control and confinement still lacking
  - Have not yet reach energy-relevant confinement or temperatures

Magnetic field is helical shaped



Reverse Field Pinch

<u>Stellarators</u> use external magnets to create the helical fields and are approaching fusion relevant conditions.

PSFC

Confinement basis:

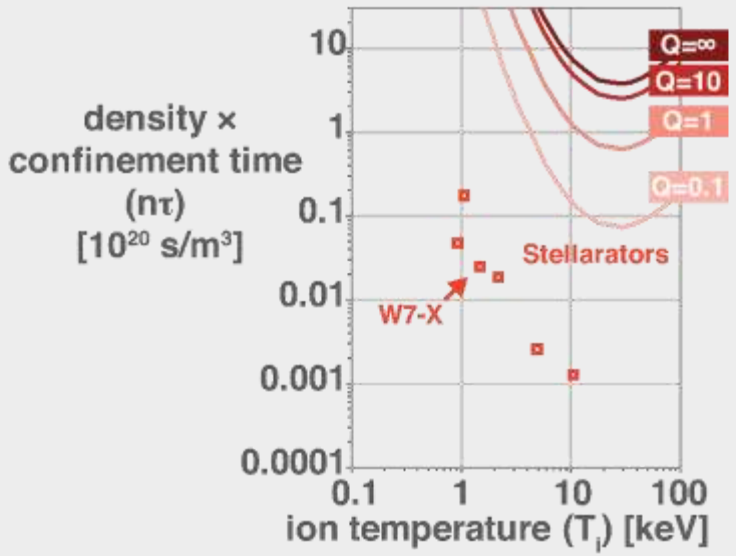
- Magnetic fields (twisted by external coils)

Active experiments:

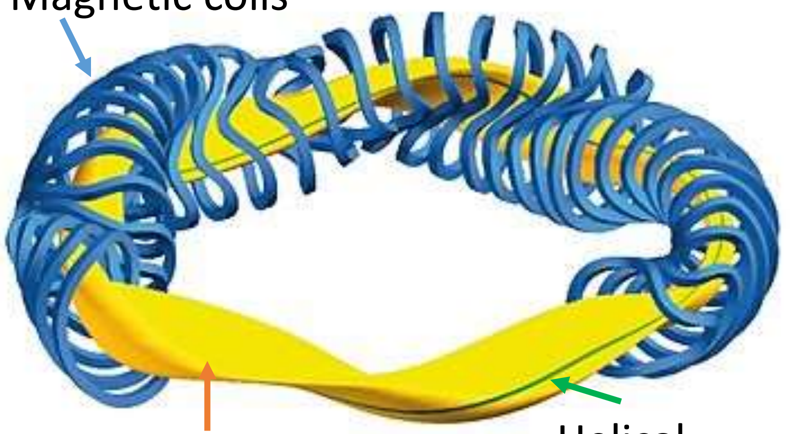
- LHD (Japan), W7-X (Germany), HSX (U. Wisc.)

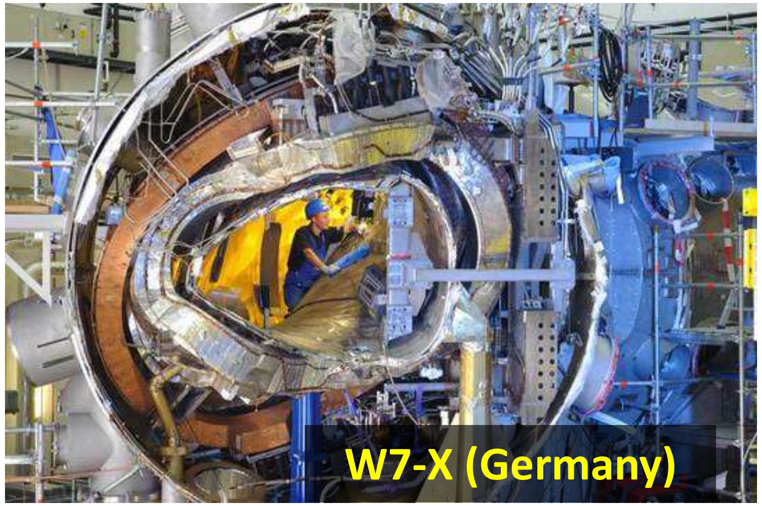
Key lessons learned:

- Good plasma performance but tough engineering



- Use many external magnetic coils to create precisely the desired magnetic field shape
  - Stable and steady-state
- Requires highly optimized field shapes and magnets to obtain best performance
  - One of the original fusion concepts
  - Ongoing work world-wide
- Higher performance but with complex engineering to create the exact right 3D shapes
  - Makes an expensive reactor





Tokamaks use the plasma and simple external coils to generate the helical magnetic field. They have performed the best.

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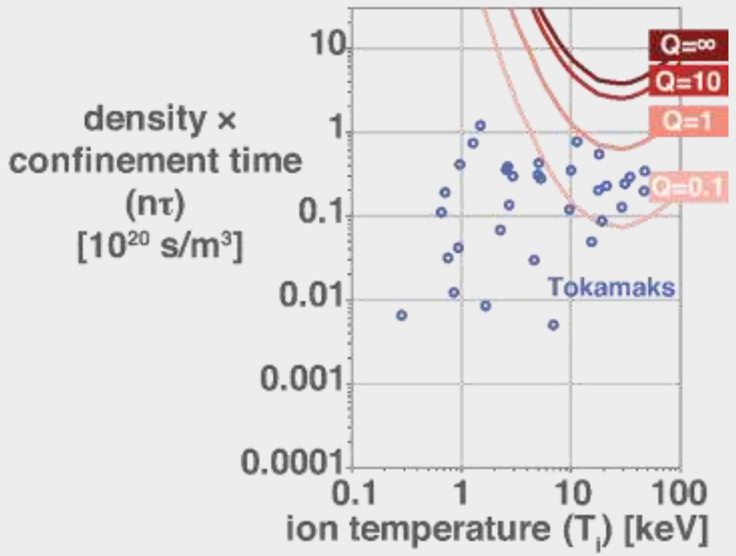
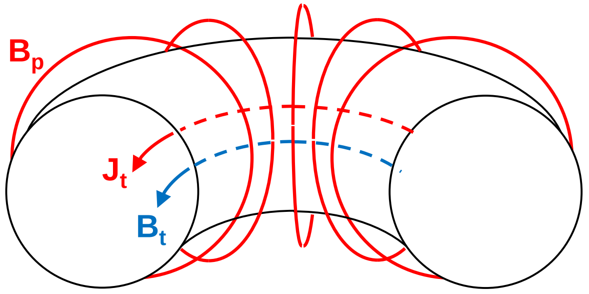
Confinement basis:
- Magnetic fields (twisted by external coils and plasma)

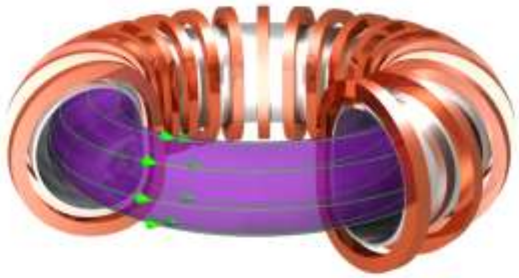
Active experiments:
- JET, ASDEX-U, DIII-D (33 worldwide)

Key lessons learned:
- Most promising candidate for fusion energy

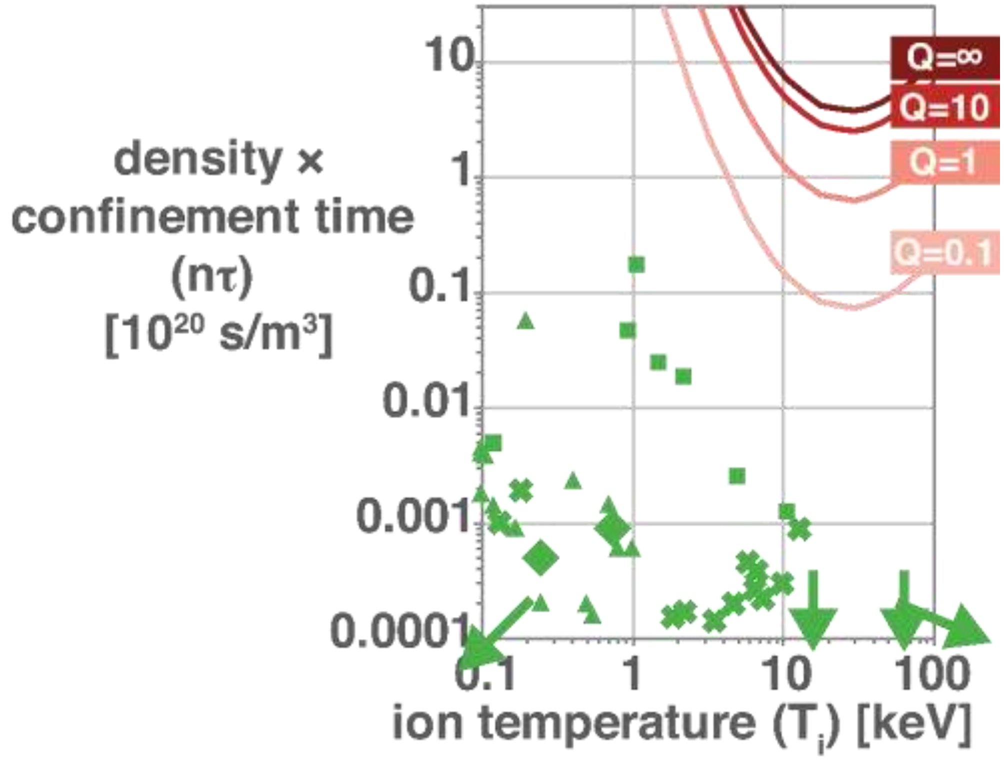


- Simplify the magnets by carrying toroidal current in the plasma to create a slightly helical field
  - Good stability and can be made steady-state
  - Symmetry provides good confinement
- High initial performance led to lots of research for the past 50 years,
  - ~170 devices built (6 at MIT)
  - Extensive physics understanding
  - Technologies well developed
  - Only devices to make significant fusion energy (17MW Q~0.65)
- Consensus among world plasma physics community is that tokamaks will be able to generate net energy





The non-tokamaks concepts just aren't there yet … some may never be.

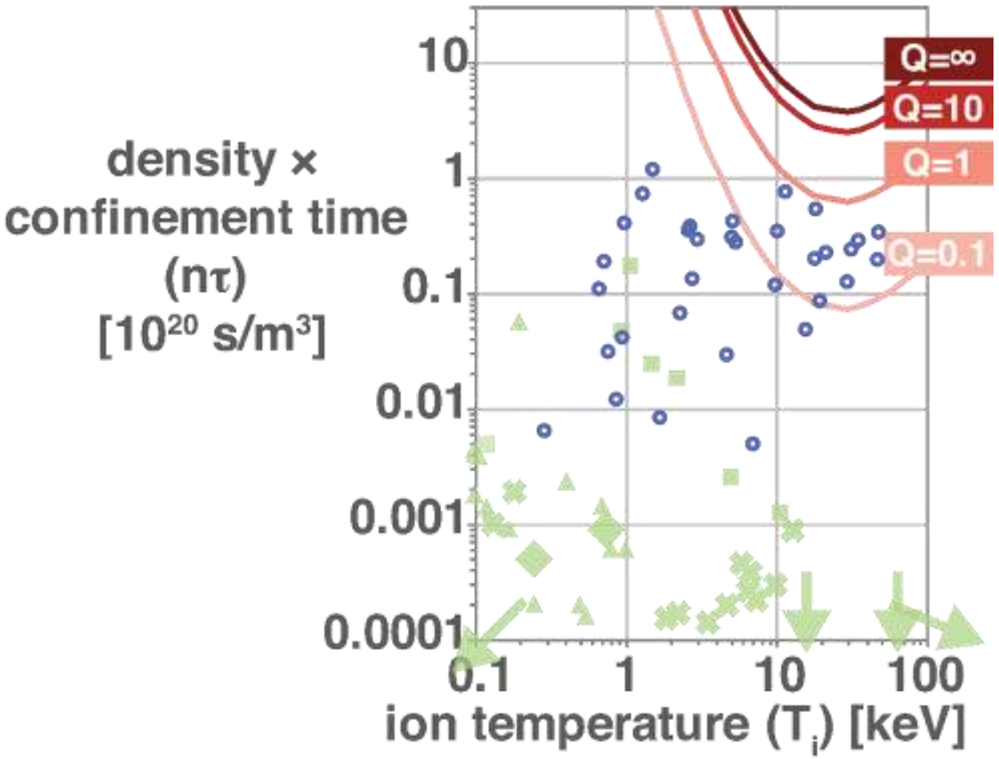


The tokamak outperforms by far all other fusion energy concepts in nTtE, justifying its claim as the leading contender for fusion energy

PSFC

Only the tokamak has demonstrated the necessary proximity to Q > 1

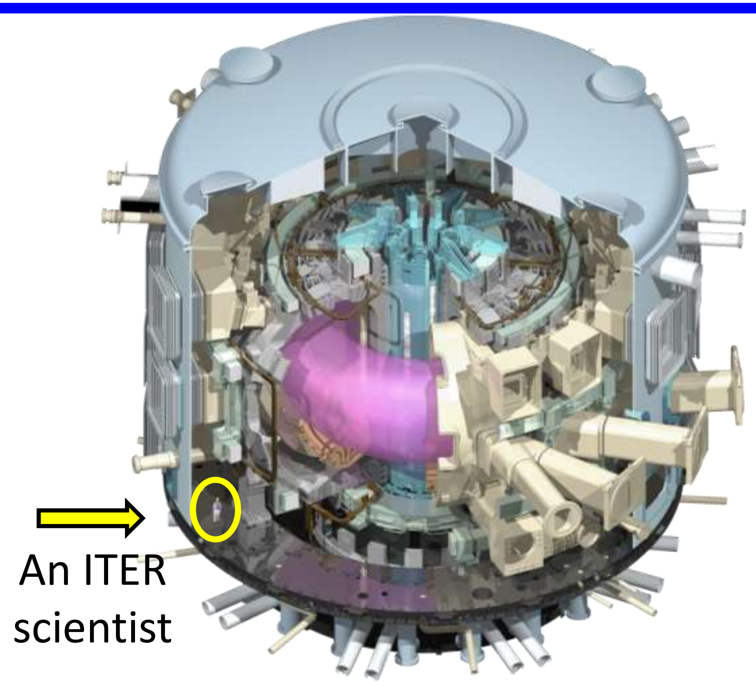
- Maximum achieved $nT\tau_E$ gave Q = 0.65 (JET, UK, 1997)
- Not quite there yet (still requires adult supervision to ride…)

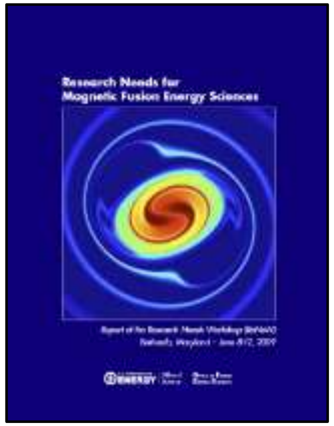


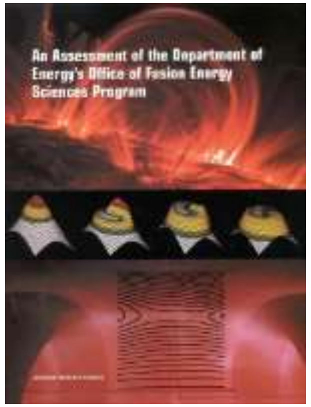
The tokamak outperforms by far all other fusion energy concepts in nTtE, justifying its claim as the leading contender for fusion energy

PSFC

ITER is **a $50 billion dollar statement of conviction** by the world's leading scientific nations and institutions that the tokamak has achieved sufficient performance and is ready to achieve net fusion energy for the first time in human history







National Academies and Blue-ribbon reports

The tokamak outperforms by far all other fusion energy concepts in nTtE, justifying its claim as the leading contender for fusion energy

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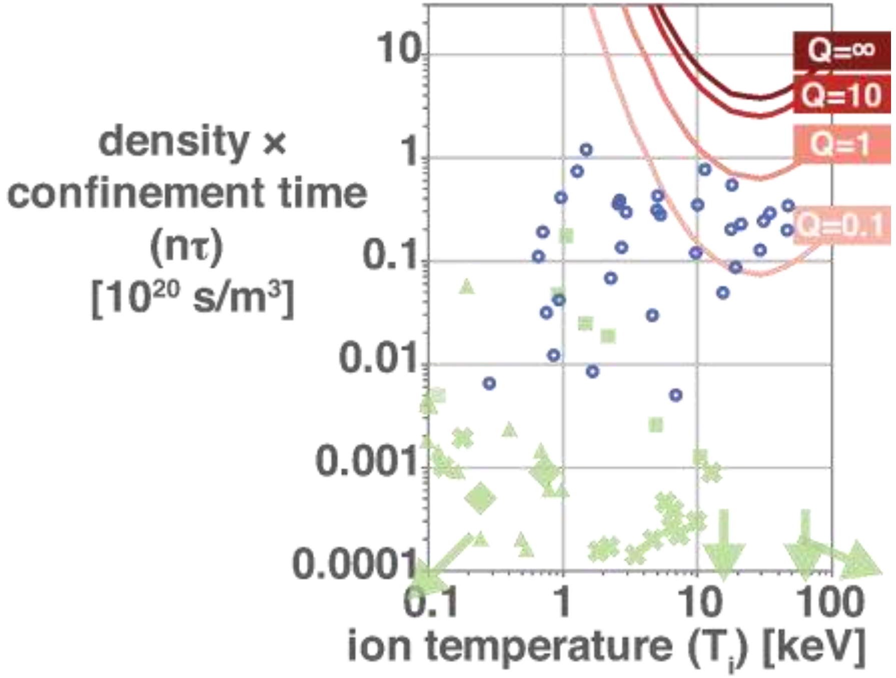
The tokamaks' physics achievements do not validate nor elevate non-tokamak concepts' claim to be nearing the production of fusion energy.

- They continue to be very interesting scientifically but need much progress to demonstrate energy relevance



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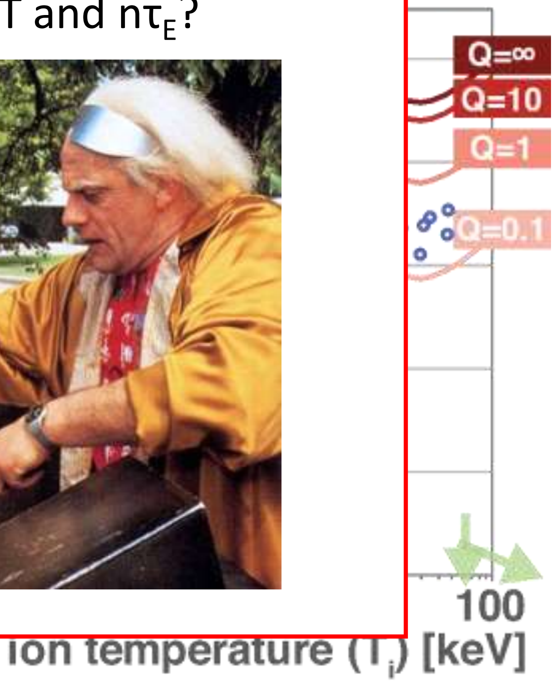
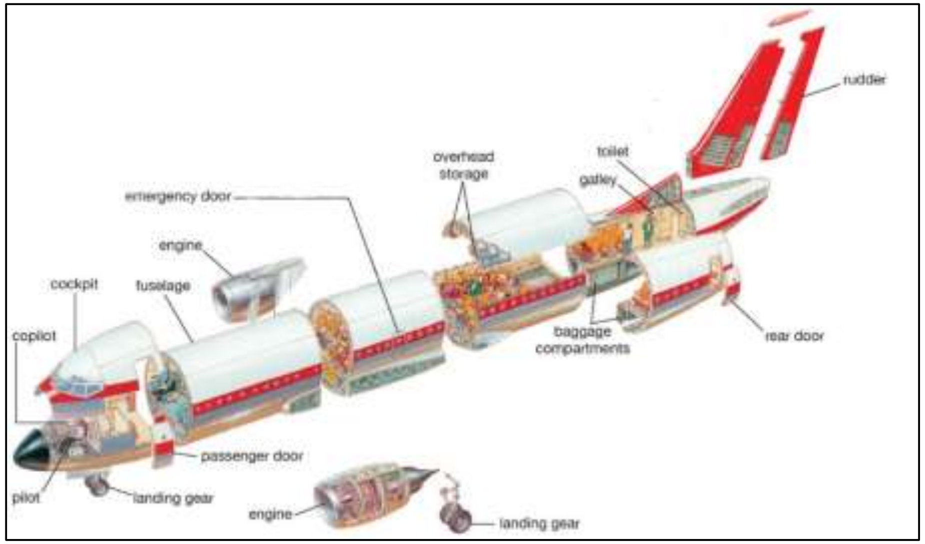


The ability to evaluate complicated technology is about asking the right questions

Flight

Pitch: It's deluxe transportation!
You : Yes, but … where's your wing?



Fusion energy

Pitch: Look at this amazing reactor design!
You : Yes, but … what's your T and $n\tau_E$?

Mr. Fusion

PSFC

Q3: What fusion energy approaches exist and how should they be evaluated?

Rule 3

Many approaches to fusion energy have been/are being tried;
only the tokamak has demonstrated energy-ready performance.

The tokamak ($nT\tau_E$ giving Q ~ 0.65) leads by a lot.
Stellarators come next and will be interesting to watch.
All others a very distant (factor of 10^4 – 10^6) third.

Questions to ask:

"Has this approach been tried before? Why was it previously abandoned?"
"How far in $nT\tau_E$ are they extrapolating to show energy-relevance?"
"How do they propose achieving a 10^4 to 10^6 needed $nT\tau_E$ improvement?"
"What cost and time were historically required to make $nT\tau_E$ improvement?

The Rules for assessing fusion energy concepts

Rule 1

Fuel choice fundamentally sets the difficulty of any approach to fusion energy.

Rule 2

Proximity to burning plasma conditions is the ultimate arbiter of the viability of any fusion energy approach.

Rule 3

Many approaches to fusion energy have been/are being tried; only the tokamak has demonstrated energy-ready performance.

Part 1 : Developing "The Rules" for assessing fusion energy concepts

- Q1: What are the viable fusion fuels and how do they affect the approach?
- Q2: What are the physical conditions required to achieve net fusion energy?
- Q3: What fusion energy approaches exist and how should they be evaluated?

Part 2 : MIT's accelerated pathway to demonstrate net fusion energy

The tokamak **has** demonstrated physics performance but all is not well with the tokamak. ("Tokamaks got 99 problems but $nT\tau_E$ ain't one.")

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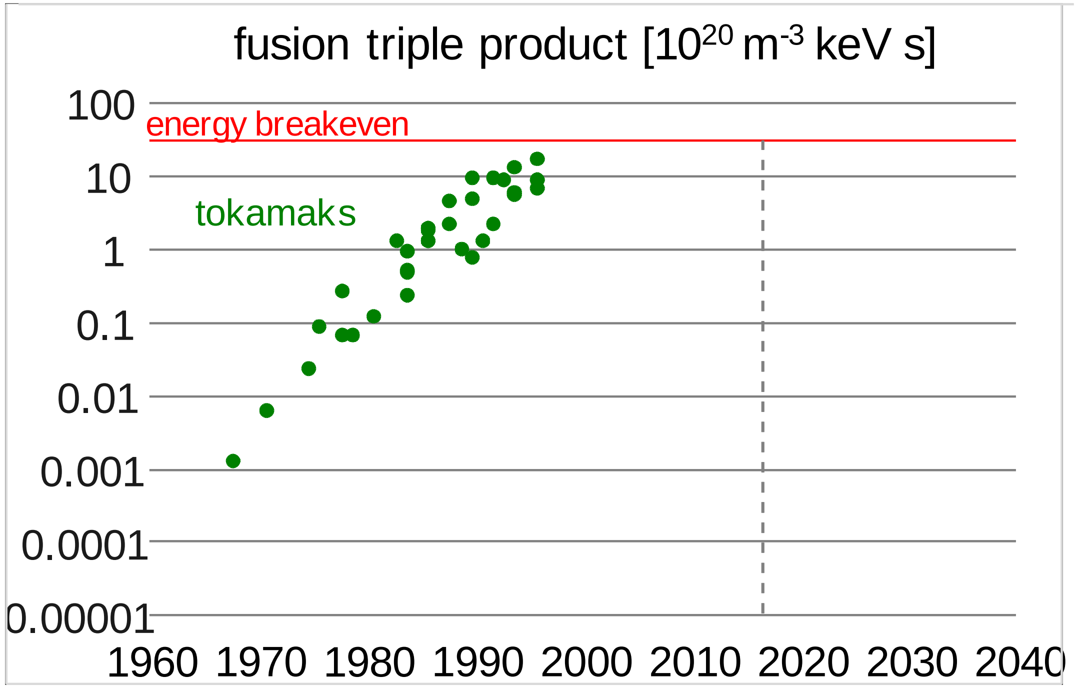
- Tokamaks made physics progress at a very rapid rate but that progress ceased after the late 1990

- **Key question:** What caused nTt_E performance to stop?
  - Did tokamaks hit a performance limit?
  - Encounter some insurmountable instability?
  - Unknown unknown fundamental physics issue?



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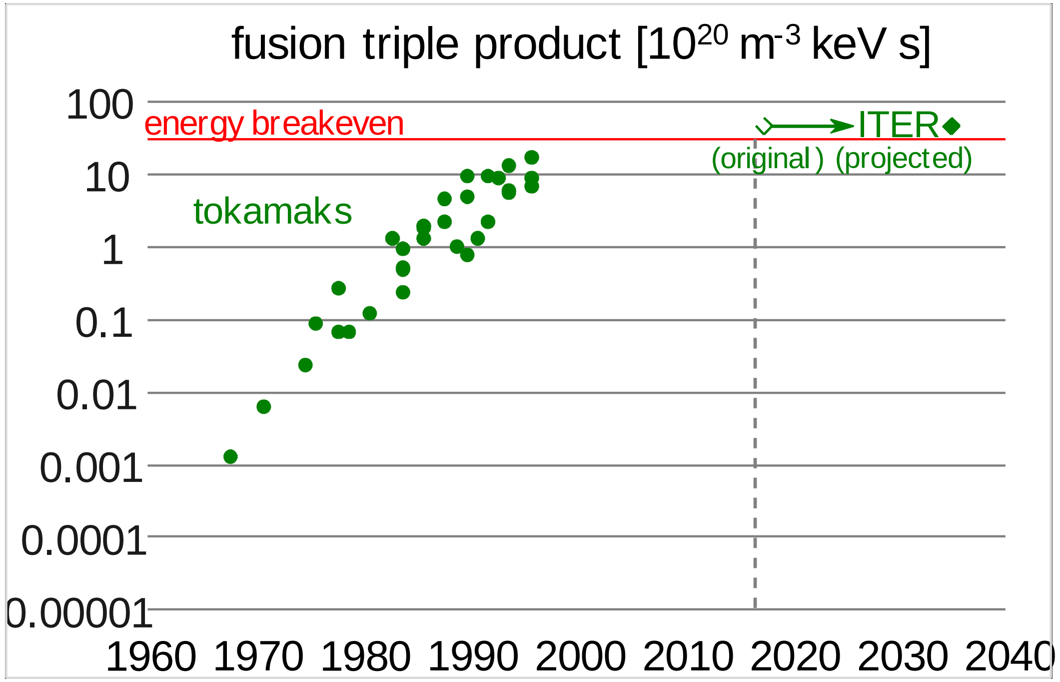
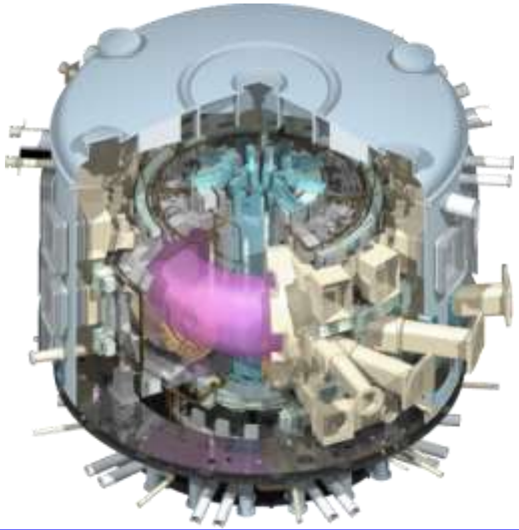
- Tokamaks made physics progress at a very rapid rate but that progress ceased after the late 1990
- Key question: What caused nTt_E performance to stop?
  - Did tokamaks hit a performance limit?
  - Encounter some insurmountable instability?
  - Unknown unknown fundamental physics issue?
- **Answer:** It stagnated due to size; it did not saturation due to any reason of physics!



JET (UK)
Peak nTt_E : 1997

This is big step

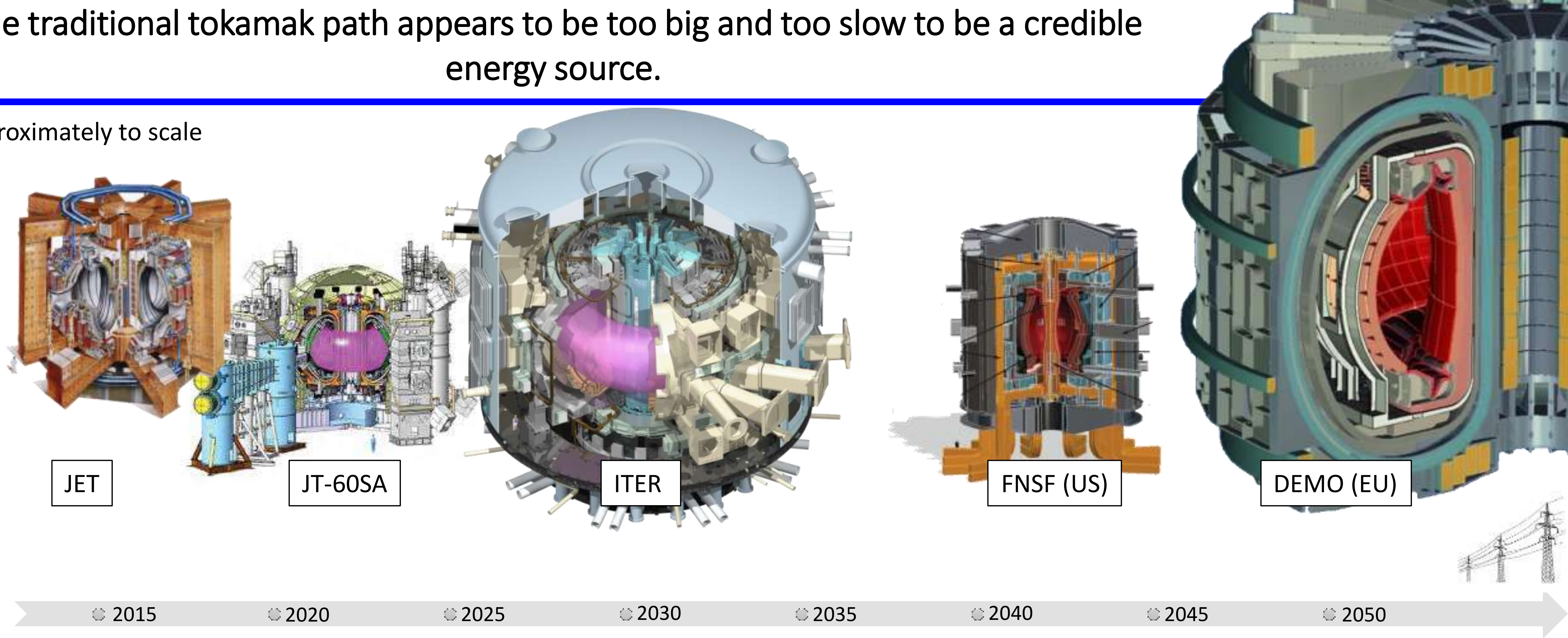


ITER (FR)
Peak nTt_E : 2040?

Human

The traditional tokamak path appears to be too big and too slow to be a credible energy source.

Approximately to scale



This graphic embodies the typical tokamak critique:

1. Tokamaks are too big
2. Tokamaks are too complex
3. Tokamaks are too slow

We completely agree and recognize that this is:

1. Caused by decisions on what tokamaks to build
2. Caused by organizational complexity at this scale
3. **Not a reason to abandon the tokamak**

Basic physics shows why increasing the magnetic field results in high fusion performance at smaller physics size

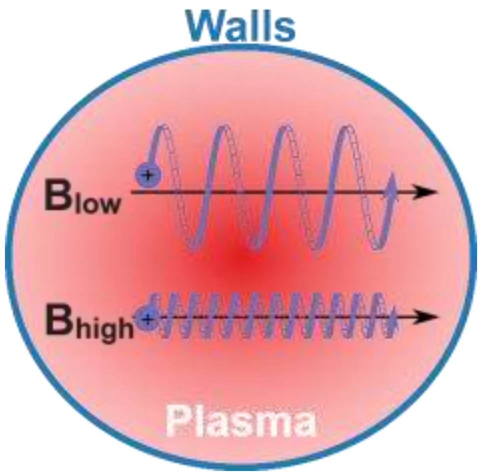
How well a plasma is insulated via the gyro-radius:

Make many of these fit inside the device →

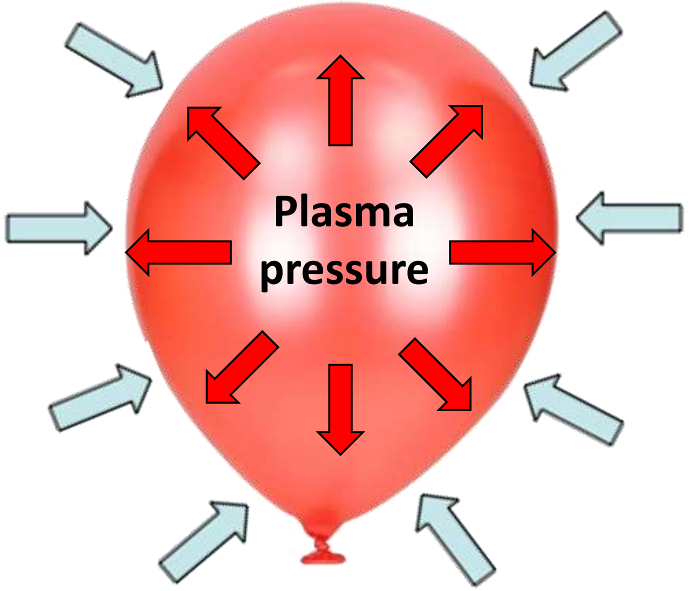
$$r_{ion} \sim \frac{\sqrt{T}}{B}$$

← Plasma temperature, set by fusion nuclear cross-section

← Magnetic field, set by device magnets



How stable the plasma is from MHD:



Magnetic pressure ~ B^2

How reactive the plasma is: Volumetric fusion rate ∝ (plasma pressure)^2 ∝B^4

ENERGY GAIN: (science feasibility)

$$\boxed{nT\,\tau_E \sim \frac{\beta_N H}{q_*^2} R^{1.3} B^3}$$

POWER DENSITY: (economics)

$$\boxed{\frac{P_{fusion}}{S_{wall}} \sim \frac{\beta_N^{\,2} \epsilon^2}{q_*^2} R B^4}$$

The impact of magnetic field plays a central role in determining the feasible size of a fusion device that achieves Q>1

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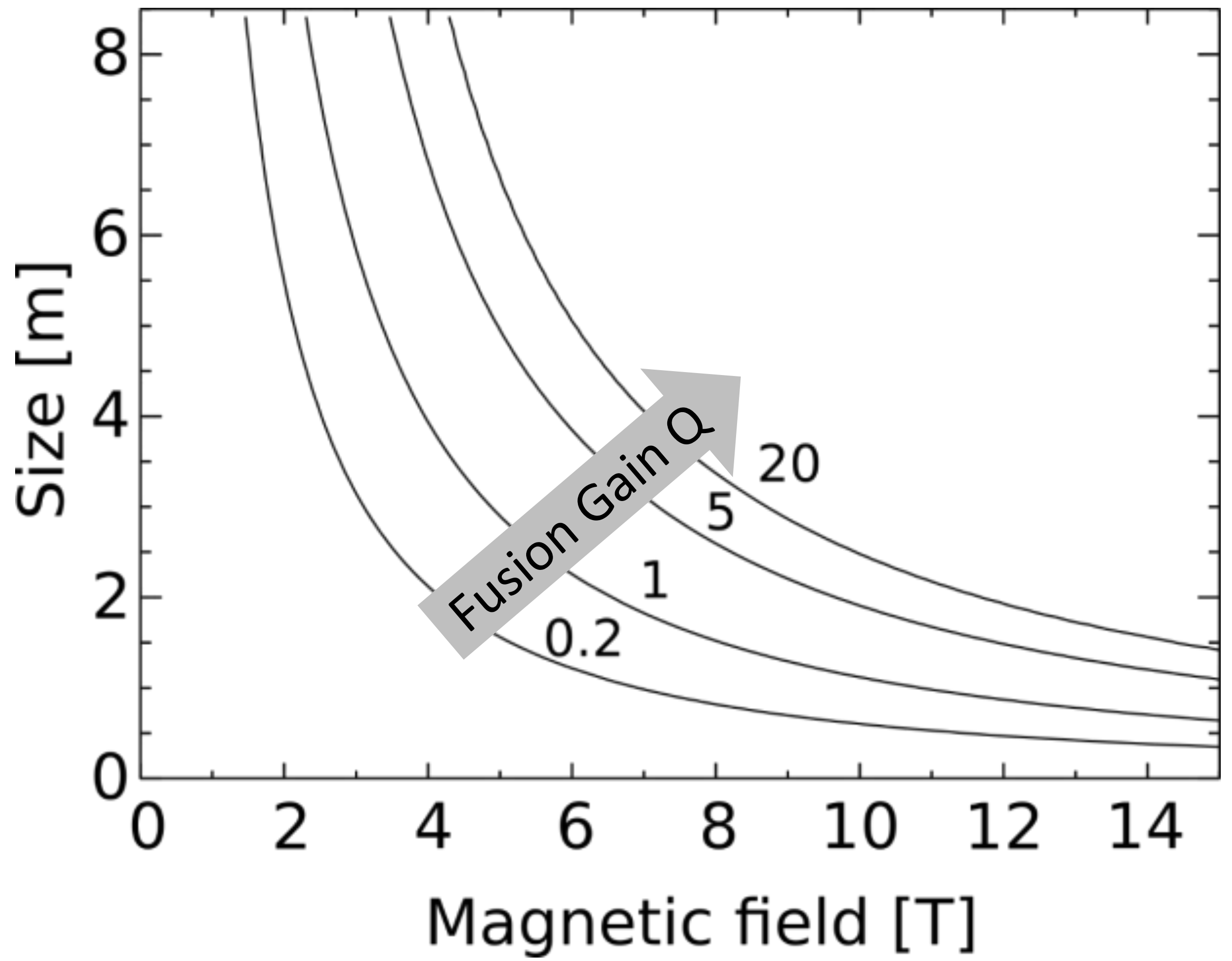
Global scale

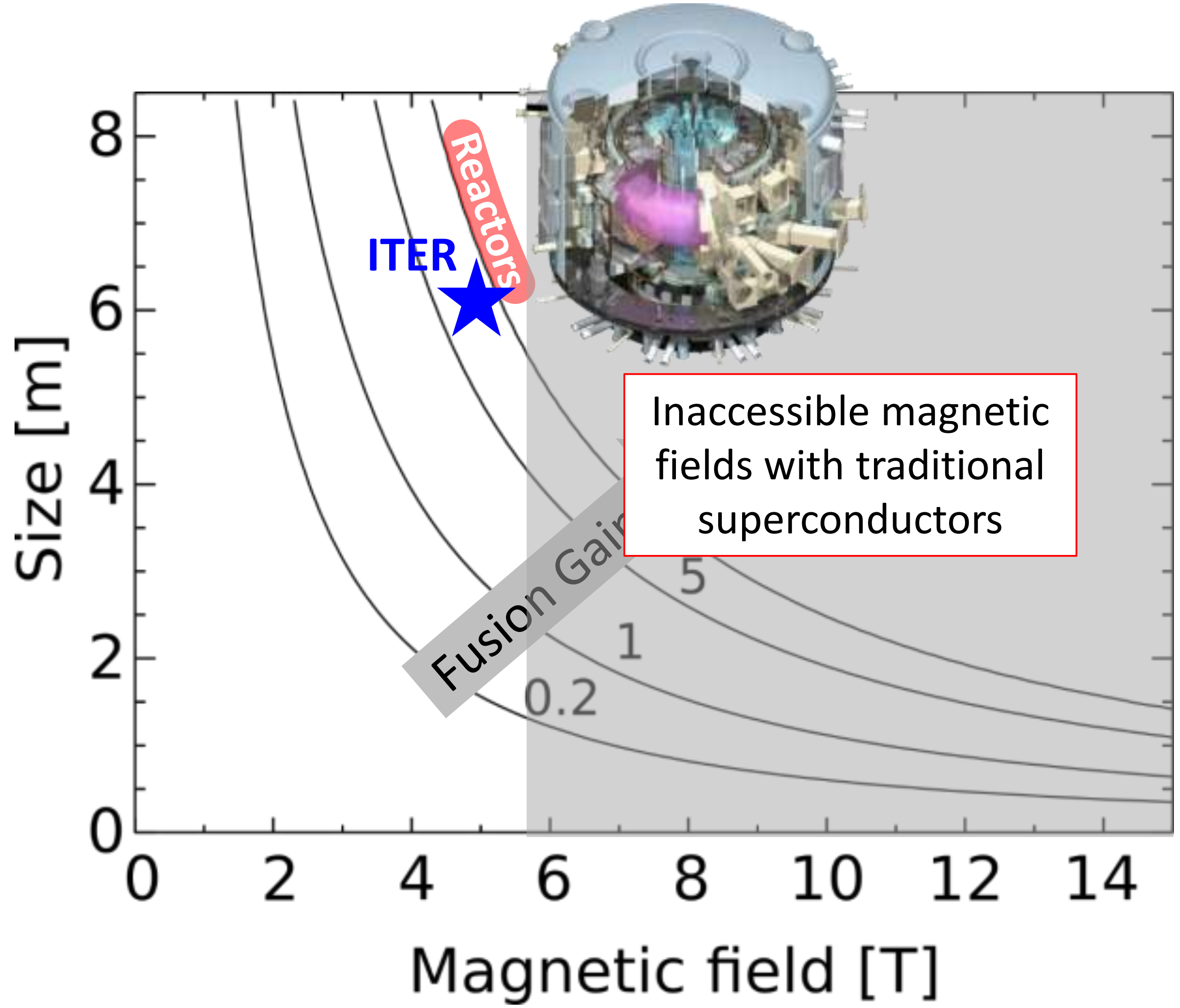
National lab scale

University/company scale



The combination of plasma physics and ITER's choice of magnet technology fundamentally constrains it's size … therefore, cost, timeline, complexity…

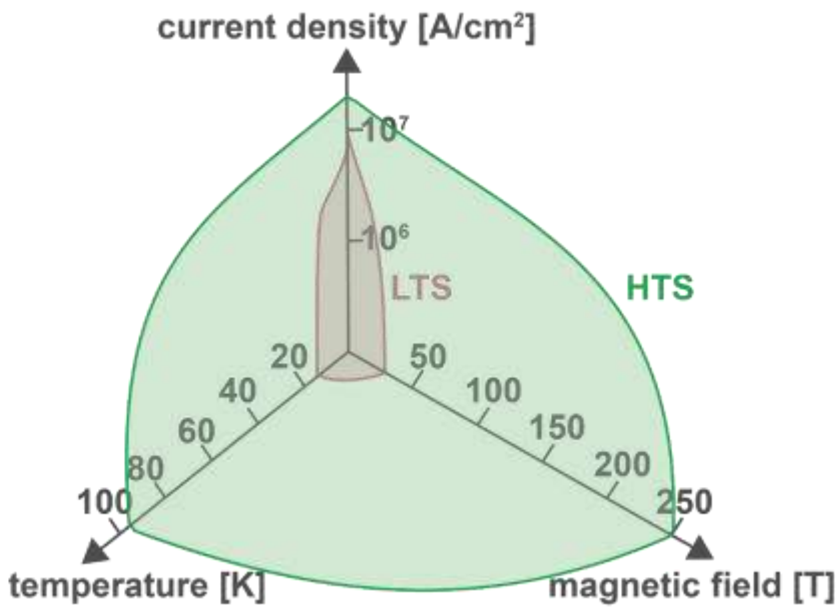
PSFC



Recently, a completely game-changing innovation has come to industrial maturity: superconductors that enable very high field magnets

PSFC

- High-temperature superconductors (HTS) are a step-change in superconducting technology over low-temperature superconductors (LTS)
  - Construction of much higher field magnets
  ⟹ Dramatically reduce fusion size/increase performance
  - Operation at higher temperatures
  ⟹ New cryogenic options, better material properties
  - Higher current densities
  ⟹ More compact magnets with stronger structure



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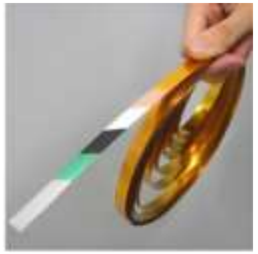
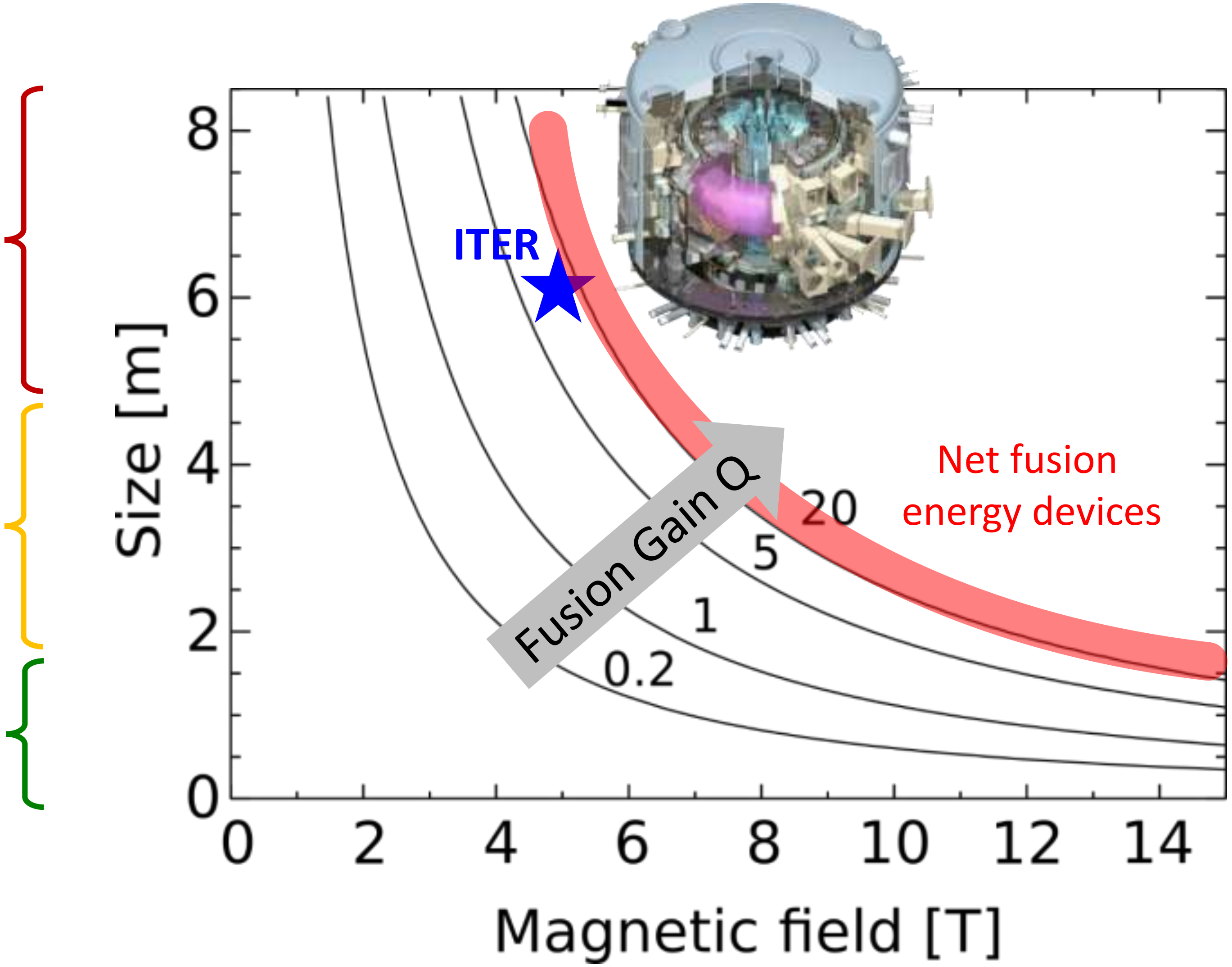
- HTS has only recently become **an industrially produced** product **with sufficient performance** for use in very high-field fusion magnets

amsc
THEVA
SuNAM
STI
BRUKER
deutsche nanoschicht
MetOx
SuperOx
Fujikura
SuperPower Inc. A Furukawa Company



The successful construction of HTS magnets opens the path to achieving net fusion energy gain devices at significantly smaller size

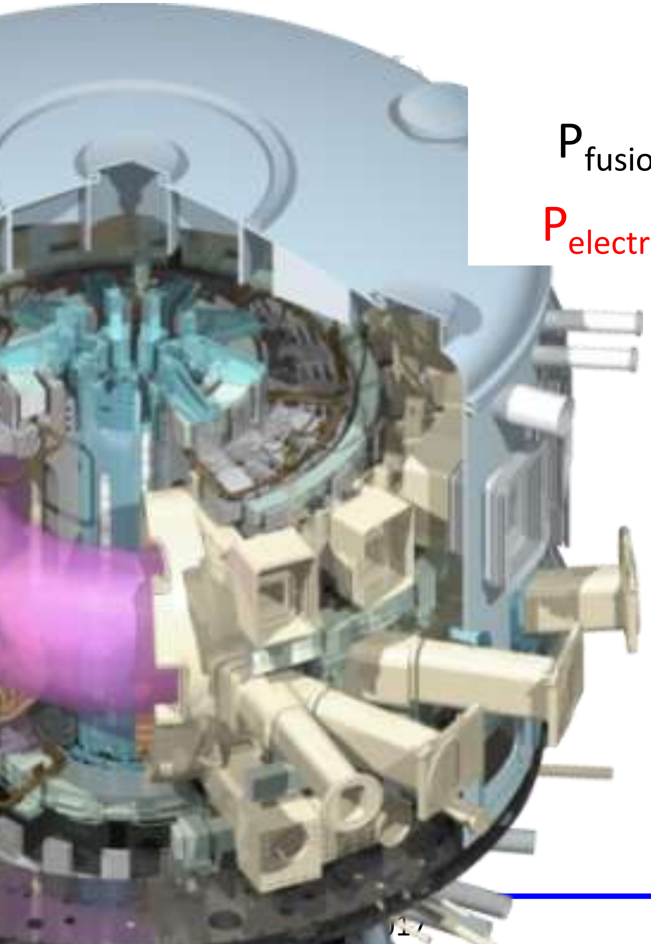
PSFC



Higher field HTS magnets would enable ARC (a conceptual design) to produce the same fusion power as ITER in a device roughly ~10 times smaller in volume

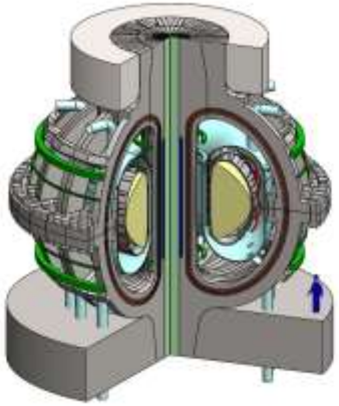
PSFC

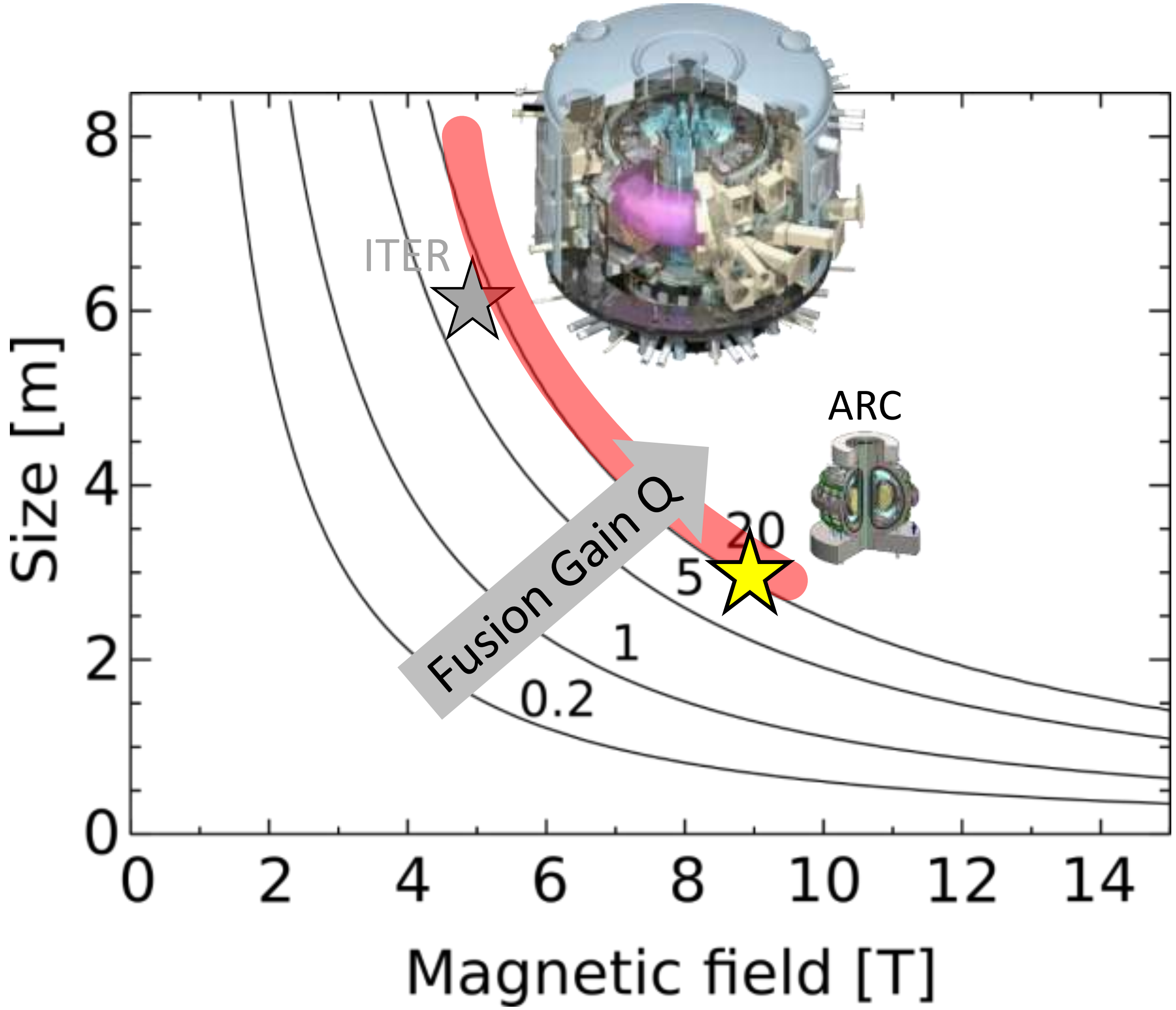
ITER



	ITER	ARC
R [m]	6.2	3.2
Magnet	LTS	HTS
B [T]	5.3	9.2
P_{fusion} [MW]	500	500
$P_{electric}$ [MW]	0	200

ARC



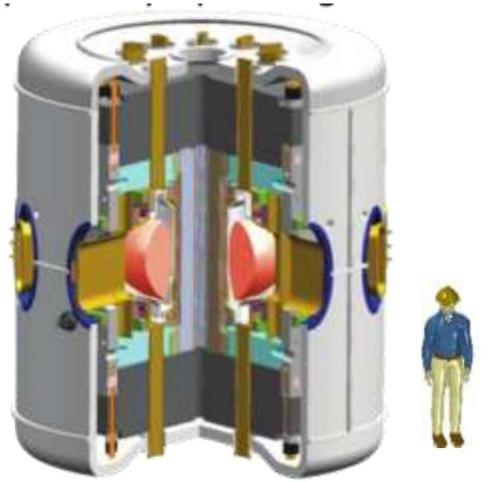


Higher field HTS magnets will enable SPARC to achieve net energy fusion gain (Q > 2) in a university-scale tokamak.

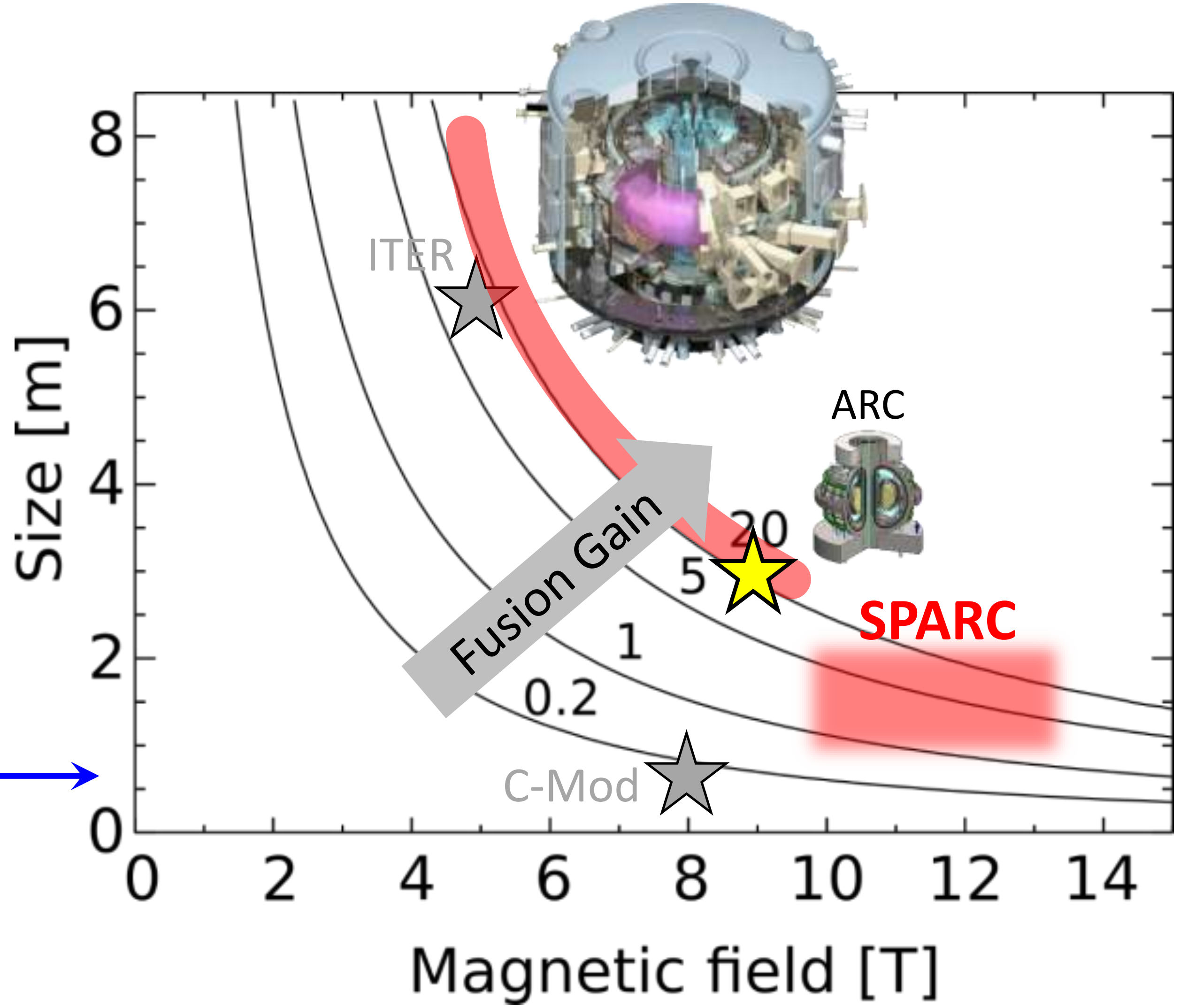
PSFC

If higher magnet fields enable ARC to rethink how fusion energy tokamaks are designed … why stop there?

SPARC (Smallest Possible ARC) will make the logical next step and be about twice the size of Alcator C-Mod

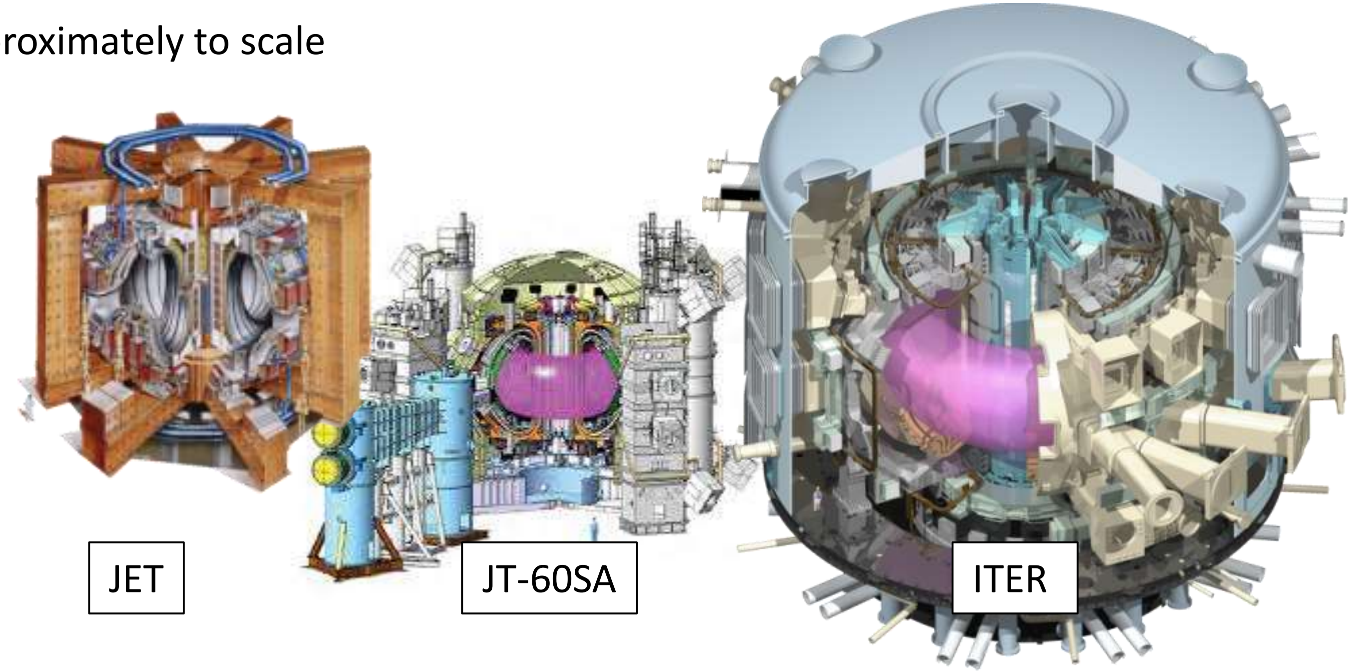


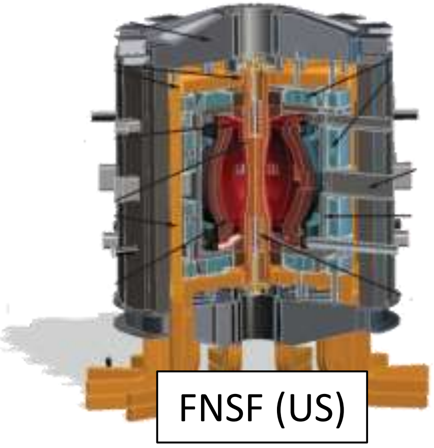
Alcator C-Mod
(MIT PSFC)

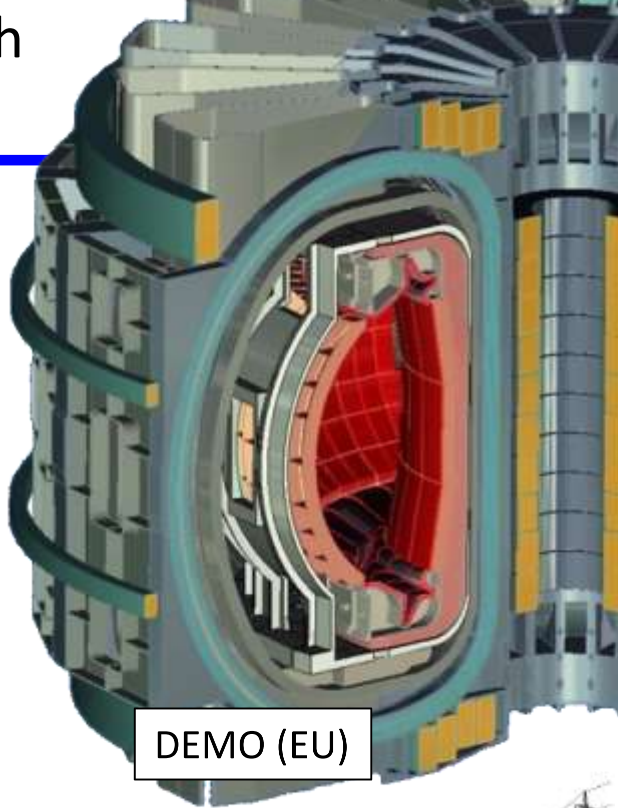


The PSFC is combining the superior physics performance of the tokamak with game-changing magnet technology to accelerator the path to fusion energy

Approximately to scale







Tokamaks without HTS: Moderate field, large size

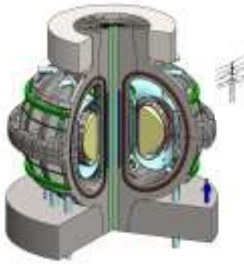
2015 · 2020 · 2025 · 2030 · 2035 · 2040 · 2045 · 2050

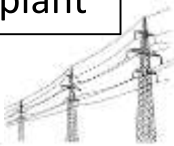
Tokamaks with HTS: High field, small size

C-Mod

SPARC →

ARC FNSF/pilot plant





Higher field → Smaller size → Lower cost →
Easier to try → Faster to learn →
Faster to burn → Faster to earn →
Faster to make a difference

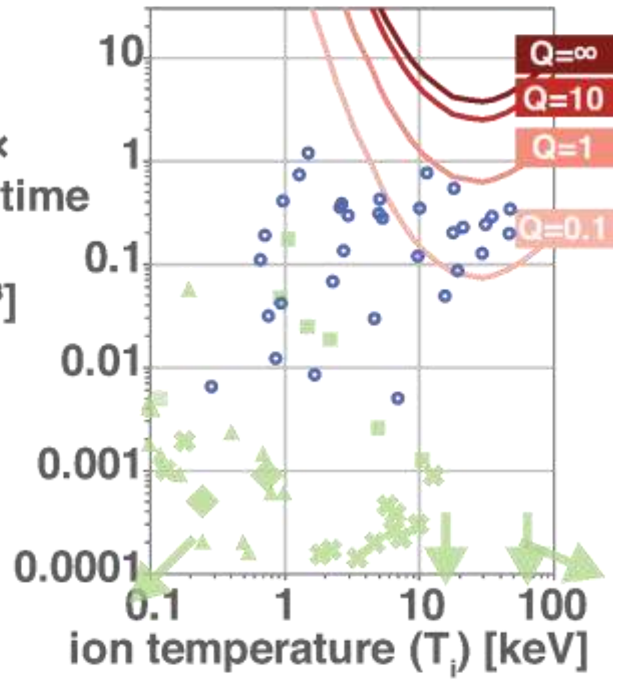
Conclusion

PSFC

Always ask:

"What does your wing look like?"

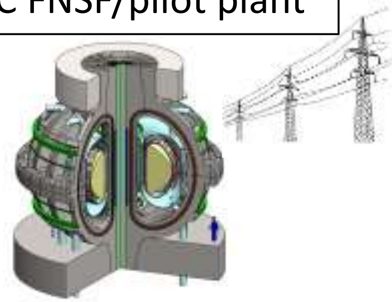
"What is your $n\tau_E$ and T?"



C-Mod

SPARC

ARC FNSF/pilot plant



Backup